STUDIES ON FLOW THROUGH NOZZLES WITH SUDDEN EXPANSION

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CERTIFICATE

Certified that the work contained in the thesis entitled "*Studies on Flow through Nozzles with Sudden Expansion*", by "*Krishna Murari Pandey*", has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

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ABSTRACT

Airflow from convergent and convergent–divergent axisymmetric nozzles expanded suddenly into a circular duct of larger cross-sectional area than that of nozzle exit area were studied experimentally, focussing attention on the base pressure and the flow development in the enlarged duct. The flow parameters considered in this investigation are the Mach number at the nozzle exit and the primary pressure ratio (defined as stagnation pressure in the settling chamber to that of ambient atmosphere to which the flow from the suddenly expanded ducts were discharged). The geometrical parameters considered were the area ratio between the sudden expansion duct cross–section and the nozzle exit area and the length to diameter ratio of the enlarged duct. To investigate the influence of passive control on the base as well as on the flow field developing in the enlarged duct, passive controls in the form of annular rectangular cavities were provided at different locations along the length of the enlarged duct at its inner surface. The cavity aspect ratio (the width to depth of the cavity) used were 1 and 2.

The Mach numbers used in the present study were in the range from 0.60 to 2.75. The area ratio covered ranges from 2.89 to 10. The primary pressure ratios used were in the range from 1.28 to 3.48. The length to diameter ratio of the enlarged duct was varied from 1 to 10. To investigate the effect of the flow quality at the nozzle exit on the base and on the flow developing in the enlarged duct, two kinds

of supersonic nozzles in the form of straight convergent-divergent and the de Laval nozzles were studied. In all the cases, in addition to base pressure and wall pressure measurement, the pressure loss was also measured by measuring the total pressure at the exit of the enlarged duct.

The experimental investigation on suddenly expanded flow field covering the above flow and geometrical parameters revealed that the base pressure is strongly influenced by the parameters *viz.* the nozzle exit Mach number, the area ratio of the passage and the length to diameter ratio of the enlarged duct. The base pressure is found to be oscillatory for flow from straight convergent-divergent nozzles, whereas for flow from Laval nozzles the oscillations are insignificant. The base pressure increases with increase in Mach number in the supersonic range whereas in the subsonic range it decreases with increase in Mach number. The annular cavities are found to increase the base pressure with increase in their aspect ratio. The length to diameter ratio beyond 6 is of no significant influence on the base pressure. The effect of cavity on wall pressure development in the enlarged duct is significant for subsonic Mach numbers, whereas for supersonic Mach numbers the effect is only marginal. The wall pressure development in the enlarged duct revealed that the duct should have more than a definite minimum length for proper development of the flow.

The total pressure loss increases with increase in Mach number, primary pressure ratio, area ratio and L/D ratio. Pressure loss is more for convergent-divergent nozzles compared to Laval nozzles. For a given primary pressure ratio and area ratio there exists a definite critical length of the enlarged duct giving a maximum secondary vacuum at the base and a minimum pressure loss.

SYNOPSIS

Introduction

Flow through nozzle which is expanded abruptly into a duct of larger area is an interesting gasdynamic problem with a wide range of practical applications. As such, it has been the subject of research to a large number of investigators over many decades. Studies on this problem have been conducted both in compressible and incompressible flows. Extensive experimental and some theoretical/emperical correlations are available for specific cases to predict this phenomenon fairly well in the subsonic regime of the flow. However, not much work has been reported for flows in the supersonic regimes. The present study is an experimental investigation on this problem scanning a range of Mach number from subsonic to supersonic values. In addition, passive contols in the form of annular rectangular grooves were introduced into the enlarged duct to study their influence on the base pressure and on the flow development in the enlarged duct.

Experimental study of flow through nozzle with sudden enlargement

The present work is concerned with air jets from convergent, convergent–divergent and Laval nozzles suddenly expanded into a circular tube of cross-sectional area

larger than that of nozzle exit, which discharges into the atmosphere. Studies were made with the enlarged duct with smooth inner surface and with annular rectangular cavities at specified locations along its length. It is observed from literature that, so far, the investigators only aimed at studying the base pressure, mostly for specific values of Mach numbers at the entry to the enlargement. Few attempts [60] were made to study the effect of passive control in the form of annular cavities. However, these studies were only for subsonic Mach numbers. Therefore, it was decided to conduct tests on a number of experimental models with different area ratio and L/D ratio, covering a range of nozzle exit Mach numbers from subsonic to supersonic values to decide on the critical length of the enlargement giving maximum secondary vacuum with smooth flow development in the enlarged duct with and without passive controls. An experimental facility as shown schematically in figure - 1 in chapter 3 has been used for the study. For measurement of stagnation and static pressures, long column 'U' tube and multichannel mercury manometers, respectively were used. The base pressure, the stagnation pressure at the settling chamber, the total pressure at the exit of the enlarged duct and complete wall static pressure along the length of the enlarged duct were measured. The nozzles used gave Mach numbers of 0.60, 0.82, 0.96, 1.00, 1.58, 1.74, 2.06, 2.23, 2.40 and 2.75. The length of the enlarged ducts varied from one diameter to ten diameters in steps of one diameter. The ratio of the enlarged duct area to nozzle exit area was varied from 2.89 to 10 and measurements were made with area ratios of 2.89, 6 and 10. The annular rectangular cavity aspect ratio, defined as the ratio of cavity width to depth was varied from 1 to 2.

Results

The main results of the present experimental study are the following:

1. The base pressure is strongly influenced by the geometrical parameters *viz.* the area ratio of the passage, the length to diameter ratio of the enlarged duct and also by the nozzle exit Mach number. The effect of annular cavity on base pressure is only marginal.

2. The base pressure is found to be oscillatory for flow from convergent–divergent nozzles, whereas, for flow from Laval nozzles the oscillations are almost insignificant. It is also insignificant for the flow from convergent nozzle.

3. The annular cavities are found to increase the base pressure with increase in their aspect ratio. However, for supersonic Mach numbers the base pressure decreases for cavity aspect ratio 1 and it increases for cavity aspect ratio 2, for L/D ratio upto 4. For L/D ratio more than 4, an increase in base pressure is always observed with increase in aspect ratio at all supersonic Mach numbers and for all the area ratios tested. It is also observed that the length to diameter ratio beyond 6 is of no significant influence on the base pressure.

4. Base pressure is found to increase with increasing Mach numbers in the supersonic range. In subsonic range a decrease in base pressure is observed with increase in Mach number. Considerable oscillations were observed at few primary pressure ratios for flows with supersonic Mach numbers. Influence of cavities is less pronounced for flows with high Mach numbers. It was also found that the base pressure behaviour was smooth and without oscillations

for flow from convergent nozzle in the Mach number range of 0.60—1.00.

5. The effect of cavity on wall pressure development in the enlarged duct is marginal at supersonic flows whereas it is significant for subsonic Mach numbers. The wall pressure distribution in the enlarged duct revealed that the duct should have a definite minimum length for proper development of the flow.

6. The effect of aspect ratio on wall pressure is only marginal for supersonic Mach numbers, whereas it is considerable for subsonic Mach numbers resulting in the suppression of the oscillatory nature of wall static pressure field, thereby taking it smoothly from base pressure level to ambient atmosphere at the exit of the duct.

7. Total pressure loss increases with increase in Mach number, primary pressure ratio, area ratio and L/D ratio. In supersonic regime pressure loss increases for models with cavity aspect ratio 1 and decreases for models with cavity aspect ratio 2 for L/D ratio upto 4. Pressure loss is more for convergent–divergent nozzles in comparison to nozzles with method of characteristics contour.

8. For a given primary pressure ratio and area ratio there exists a definite critical length of the enlargement giving a maximum secondary vacuum and a minimum pressure loss.

Contents of the thesis

This thesis consists of five chapters and two appendices. A detailed bibliography is also provided. In chapter 1 the problem undertaken to be studied has been briefly described. This is followed by a literature survey related to the present problem.

The experimental set–up used in the investigations undertaken has been discussed in detail in chapter 3. The various data thus gathered have been analysed and appropriately presented, graphically or otherwise in chapter 4. The conclusions of the thesis form the body of chapter 5. Appendix A discusses some details of accuracy considerations in the present experimental set–up. Appendix B identifies further scope of work on similar lines based on the experiences gained by the author during the stages leading to this dissertation.

NOMENCLATURE

D Diameter of the enlarged duct.

L Length of the enlarged duct.

H Depth of the cavity.

W Width of the cavity.

$\mathbf{d_t}$ Nozzle throat diameter .

$\mathbf{d_o}$ Nozzle exit diameter .

M Nozzle exit Mach number.

W/H Cavity aspect ratio.

L/D Length to diameter ratio of enlarged duct.

X Distance of the location of the pressure tapping along the enlarged duct length.

X/L Ratio of distance of the location of the pressure tappings to the total length of the enlarged duct.

ST Models with smooth inner surface.

ASR1 Models with annular cavity aspect ratio 1.

ASR2 Models with annular cavity aspect ratio 2.

$\mathbf{P_a}$ Atmospheric pressure.

$\mathbf{P_b}$ Base pressure.

$\mathbf{P_w}$ Wall pressure.

$\mathbf{p_{01}}$ Total pressure in the settling chamber.

$\mathbf{P_{02}}$ Total pressure at the exit of the enlarged duct.

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Chapter 1

INTRODUCTION

1.1 Introduction

The sudden expansion problem both in subsonic and supersonic regimes of flow is of general interest with a wide range of applications. The use of a jet and a shroud configuration in the form of a supersonic parallel diffuser is an excellent application of sudden expansion problems. Another interesting application is found in the system used to simulate high altitude conditions in jet engine and Rocket engine test cells; a jet discharging into a shroud and thus producing an effective discharge pressure which is subatmospheric. A similar flow condition exists in the exhaust port of an internal combustion engine, the jet consisting of hot exhaust gases passing through the exhaust valve. Another relevant example is to be found in the flow around the base of a blunt edged projectile in flight where the expansion of the flow is inward rather than outward as in the previous example.

1.2 Outline of the thesis

The abrupt expansion of a jet of gas is a problem of general interest which occurs in a variety of flow systems. The configuration of a jet and duct is used as a supersonic parallel diffuser. However in most of the cases the enlarged duct used has a smooth continuous inner surface. The present work is mainly concerned with air jets expanding into short lengths of duct with cavities and finally discharging into the atmosphere. The pressure ratio across the duct, nozzle exit Mach number, the length to diameter ratio(width to depth) of the cavity were treated as independent parameters. The base pressure, flow development in the enlarged section and total pressure loss were systematically investigated. Oscillations of the base pressure were also studied. The jet was discharged into the atmosphere and the investigation was carried out for the following values of pressure ratios; 2.10, 2.38, 2.65, 2.93, 3.21 and 3.48. Three different models having area ratios of 10, 6 and 2.89 were tested. For all the models the length to diameter ratio of the enlargement portion was varied between 1 and 10 in steps of 1. Three types of models were tested; models without cavities i.e. models with smooth inner surface along the enlarged duct length (ST), models with cavities of aspect ratio 1 (ASR1) and models with cavities of aspect ratio 2 (ASR2). For the convergent nozzle, the pressure ratio was varied from 1.28 to 3.48, in the steps of 0.28.

In total 6 nozzles with Mach numbers 2.75, 2.40, 2.23, 2.06, 1.74 and 1.58 were tested. One convergent nozzle was also tested for Mach numbers .60, .82, .96 and 1.00. Out of these seven nozzles three had method of characteristics contours after the throat, three nozzles were straight conical type with short diffusing passage, the angle of diffuser being 10. The seventh nozzle was convergent straight conical type. Each nozzle had exit diameter 10 mm and throat was varied from 5.5 mm to 9 mm

to obtain different values of Mach numbers. The cavities of aspect ratio 1 had width and depth both 3 mm. The cavities of aspect ratio 2 had width 6 mm and depth 3 mm.

In the continuum regime, for the flow through a sudden enlargement in a tube, a wide range of experimental data and theoretical and empirical correlations to predict the flow parameters are available in literature. However, the available experimental data for models with cavities (known as passive control) is very few. Further, most of the work reported in literature is for a particular value of nozzle exit Mach number. The above status of the problem is the cause for the modest experimental investigation of the present study to fill up some of the vital gaps in the literature database.

Chapter 2

LITERATURE REVIEW

The flow field of abrupt axi-symmetric expansion is a complex phenomenon characterized by flow separation, flow recirculation and reattachment. Such a flow field may be divided by a shear layer into two main regions, one being the flow recirculation region and the other the main flow region. The point at which the dividing streamline strikes the wall is called the reattachment line.

There is a large amount of data about sudden expansion problems in literature. However, they are for specific cases for flow and geometrical parameters. It will become voluminous if the entire literature is scanned in this chapter. Therefore, the information which is directly associated with the present investigation only is reviewed here.

Borda [1] seems to be the first to investigate the problem of sudden enlargement in flow of water through sudden increase in duct cross-section. Nusselt [1] appears to be one of the first to conduct experiments with high velocity gas flow through ducts with sudden increse in flow cross-section. From his intensive experimental study in subsonic and supersonic flow, he concluded that the base pressure will be equal to the entrance pressure if the entrance velocity is subsonic, but if the entrance flow

is supersonic, the base pressure could be equal to or less than or greater than the entrance pressure. But no attempt was made by Nusselt to determine the factors governing the base pressure.

The effect of boundary layer on sonic flow through an abrupt cross-sectional area was studied by Wick [1]. He observed experimentally that the pressure in the corner of expansion was related to the boundary layer type and thickness upstream of the expansion. He considered boundary layer as a source of fluid for the corner flow. But in view of Hoerner [1] the boundary layer was an insulating layer that reduces the effectiveness of the jet as a pump.The base corner was thought of as a sump with two supplies of mass. The first was the boundary layer flow around the corner and the second source was the backflow in the boundary layer along the wall of the expanded section. This backflow occured because of the pressure difference across the shock wave originating where the jet striked the wall. He concluded that the mechanism of internal and external flow was principally the same and base pressure phenomenon in external flow could be studied relatively easily by experiments with internal flow.

Korst [2] investigated the problem of base pressure in transonic and supersonic flow for cases in which the flow approaching the base is sonic or supersonic after the wake. He devised a physical flow model based on the concepts of interaction between the dissipative shear flow and the adjacent free stream and the conservation of mass in the wake. His results agreed closely with the experimental data of Wick.

Hall and Orme [4] studied compressible flow through a sudden enlargement in a pipe both theoretically and experimentally and showed a good agreement between theoretical and experimental results. They developed a theory to predict the Mach number in a downstream location of sudden enlargement for known values and Mach number at the exit of the inlet tube, with incompressible flow assumptions. They

also assumed that the pressure across the face of the enlargement was equal to the static pressure in the small tube just before the enlargement. But this assumption is far away from the reality since it is a well established fact that the pressure across the face in the recirculation region namely the base pressure is very much different from the pressure in the smaller tube just before the enlargement. They used a nozzle and tube arrangement for the experimental and studied the problem with a range of throat Mach numbers from 0 to 1. Benedict [8, 9, 10, 12, 23] with various other investigators analyzed the sudden enlargement problem in an elaborate manner both theoretically and experimentally.

Ackeret [13] discussed special features of internal flow. He concluded that there is a predominant role played by the equation of continuity, especially if compressibility is involved and in aeronautics big deflections of the air streams are avoided as far as possible but in ducted flow, they may be quite common. If the width of the duct is not growing too fast along it's length, separation is followed by reattachment. He observed that in case of internal flows also, three dimensional boundary layers can appear as in external flow He presented the article on the aspects of the internal flow covering different types of internal flows describing some of the aspects of separation, reattachment and pressure fluctuations that are associated with sudden enlargement flows.

Anderson and Williams [14] worked on base pressure and noise produced by the abrupt expansion of air in a cylinderical duct. They used stagnation pressure ratios of the forcing jet to atmospheric of upto six for various length to diameter ratios. With an attached flow the base pressure was having minimum value which depend mainly on the duct to nozzle area ratio and on the geometry of the nozzle. The plot of overall noise showed a minimum at a jet pressure approximately equal to that required to produce minimum base pressure.

Durst, Melling and Whitelaw [20] studied low Reynold's number flow over a plane symmetric sudden expansion. The flow was depending totally on Reynold's number and the nature was strongly three dimensional. At higher Reynold's number the flow became less stable and periodicity became increasingly important in the main stream, accompanied by a highly disturbed fluid motion in the separation zones as the flow tended towards turbulence. They reported flow visualization and laser anemometry measurements. At Re of 56 the separation region behind each step were of equal length for each step but at Re of 114, the two separation regions were having different lengths leading to asymmetrical velocity profiles. At Re of 252, a third separation zone was found on one wall. There were substantial three dimensional effects in the vicinity of the separation regions.

Cherdon, Durst and Whitelaw [26] studied asymmetric flows and instabilities in symmetric ducts with sudden expansion . Asymmetric flows were caused by the disturbances generated at the edge of the expansion and amplified in the shear layers. The spectral distribution of the fluctuations in velocity are quantitatively related to the dimensions of the two unequal regions of flow recirculation. They showed that the intensity of fluctuating energy in the low Reynold's number flows can be larger than that in corresponding turbulent flows. Durst *et. al.* [20] demonstrated that symmetric flows can can exist in two- dimensional plane, symmetric, sudden-expansion ducts for only a limited range of Reynold's numbers. At higher Reynold's numbers, the small disturbances generated at the tip of the sudden expansion are amplified in the shear layers formed between the main flow and the recirculation flow in the corners. The result was a shedding of eddy-like patterns which alternated from one side to the other with consequent asymmetry of the mean flow, particularly of the dimensions of the two regions of recirculation. Although the flow was three-dimensional, it's major features could be understood by considering the interaction

of two-dimensional shear layers.

Brady and Acrivos [32] studied closed-cavity laminar flows at moderate Reynold's number. They suggested that similarity solutions should be viewed with caution because they might not represent a real flow once a critical Reynold's number was exceeded.

The flow field in a suddenly enlarged combustion chamber was studied experimentally by Yang and Yu [33]. The combustion chamber consisted of plexiglass circular duct with a suddenly enlarged section followed by a nozzle. The Reynold's number based on the inlet duct diameter and centre velocity was 6.4×10^4 . The wall pressure measurements were carried out with a laser-Doppler anemometer. Detailed profiles of mean velocities, turbulent intensities, turbulent shear stresses and wall pressure distrbution was developed. The dividing streamline, the reattachment point and the magnitudes of the mean kinetic energy and turbulent kinetic energy were also determined. They observed that the laser-Doppler anemometer with a frequency shifter was a useful instrument for measuring reverse flow fields, especially for the highly turbulent flow field encountered in the study. Measurements from a conventional hot-wire anemometer might present considerable errors.

Rathakrishnan and Sreekanth [34] studied flows in pipes with sudden enlargement. In their experiments, the flow of air from a plenum chamber to a circular cross-section constant area tube was made to expand suddenly by having an abrupt change in cross-sectional area. The pressure ratios covered ranged from 1.1 to 3 and the area ratio of the expansion was varied from 2.78 to 8.38. Length-to-diameter ratio was varied from 1 to 10. Total head pressure at the axis of symmetry at the plane of enlargement and the static pressure variation along the wall of duct were measured. They concluded that the non-dimensionalised base pressure is a strong function of the expansion area ratios, the overall pressure ratios and the duct

length-to-diameter ratios.

They showed that for a given overall pressure ratio and a given area ratio, it is possible to identify an optimal length-to-diameter ratio of the enlargement that will result in maximum exit plane total pressure at the nozzle exit on the symmetry axis (i.e. minimum pressure loss in the nozzle) and in a minimum base pressure at the sudden enlargement plane. The separation and reattachment seemed to be strongly dependent on the area ratio of the inlet to enlargement for a given nozzle and enlargement area ratio, the duct length must exceed a definite minimum value for minimum base pressure. For an optimum performance of flow through pipes with sudden enlargement, it is not sufficient if the base pressure minimization alone is considered. The total pressure loss must also be taken into account.

Raghunathan and Mabey [43] studied passive shock-wave / boundary layer control on a wall-mounted model. They evaluated the effects of the orientation of holes on the passive shock-wave / boundary layer control, incorporating three hole orientations; normal, forward facing and backward facing. The porosity used was 1.6%. Their measurements included static and dynamic pressures on the model's surface, wake traverses. They have visualized the field with shadowgraphs. The forward facing holes located around shock position showed an appreciable decrease in drag compared with solid surface model.

Raghunathan [44] studied pressure fluctuation measurements with passive shock / boundary layer control. He concluded that passive shock / boundary layer control in transonic flow could reduce pressure fluctuations in the region of shock / boundary layer interaction and hence suppresses buffeting.

Ragunathan [45] also studied the effect of porosity strength on passive shock-wave / boundary layer control and found that the forward-facing holes configuration with a porosity of 1-2% produces maximum drag reduction.

Wilcox Jr. [51] studied the passive venting system for modifying cavity flow fields at supersonic speeds. Experimentally he showed that a passive venting system could be employed to control cavity flowfields at supersonic speeds, specifically the passive venting system had been used to extend the l/h value before the onset of high drag-producing closed cavity flow. In his experiments the porous floor eliminated the large drag increase for $l/h \geq 12$. There is tremendous increase in C_D for $l/h > 12$ but for the porous floor having more diameter the decrease in C_D is comparatively very less with the floor having less diameters.

Tanner [52] studied base cavity at angles of incidence. He concluded that a base cavity could increase the base pressure and thus decrease the base drag in axisymmetric flow. He varied the angle of incidence from 0 to 25^o . At $\alpha = 2^o$, he found the maximum drag decrease.

Rathakrishnan, Ramanaraju and Padmnaban [60] studied the influence of cavities on suddenly expanded subsonic flowfield. They concluded that the smoothening effect by the cavities on the main flowfield in the enlarged duct was well pronounced for large ducts and the cavity aspect ratio had significant effect on the flowfield as well as on the base pressure. They studied air flow through a convergent axi-symmetric nozzle expanding suddenly into an annular circular parallel shroud with annular cavities experimentally. From their result it is seen that increase in aspect ratio from 2 to 3 results in decrease of base pressure but for increase in aspect ratio from 3 to 4, the base pressure goes up.

The effectiveness of passive devices for axi-symmetric base drag reduction at Mach 2 was studied by Viswanath and Patil [63]. The devices examined included primarily base cavities and ventilated cavities. Their results showed that the ventilated cavities offered significant base-drag reduction. They found 50% increase in base pressure and 3 to 5% net drag reduction at supersonic Mach numbers for a

body of revolution.

Kruiswyk and Dutton [65] studied effects of base cavity on subsonic near-wake flow. They experimentally investigated the effects of a base cavity on the near-wake flowfield of a slender two dimensional body in the subsonic speed range. Three basic configurations were investigated and compared, they are a blunt base, a shallow rectangular cavity base of depth equal to one half of the base height and a deep rectangular cavity base of depth equal to the base height. Schlieren photographs revealed that the basic qualitative structure of the vortex street was unmodified by the presence of a base cavity. The weaker vortex street yielded higher pressures in the near-wake for the cavity bases, and increases in the base pressure coefficients of the order of 10-14%, and increses in the shedding frequencies of the order of 4-6% relative to the blunt-based configuration.

It is evident from the above review that there is a need for studying the sudden expansion problems in the supersonic flow regime to bridge the gap of data in literature. Especially, suddenly expanded flow with passive control seems to be of interest with many applications. Hence the present study of the problem of suddenly expanded flow field from subsonic to supersonic regime, covering a range of geometrical parameters has been studied with and without passive controls. The passive controls choosen in the present study is rectangular annular cavities at specified locations at the inner surface of the enlarged duct. Further, supersonic flow field from convergent–divergent as well as from the Laval nozzles has been studied.

Chapter 3

EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental apparatus of the present study consists of four main components. They are (i) the compressor unit, (ii) flow system, (iii) the experimental models, and (iv) the pressure measuring instruments, as shown schematically in Fig. 1.

3.1 The Compressor Unit

The high pressure dry air required for the experimental investigation on suddenly expanded flow fields was supplied by high pressure storage tanks of 1000 cubic feet volume each. These tanks are charged by reciprocating type high pressure compressor driven by 150 HP ac motor. The compressed air from the compressor was passed through an after-cooler and then through a drier unit consisting of silica gel and electrical heaters before reaching the storage tanks. This arrangement facilitated supply of moisture free dry air at high pressure for the experimental runs. For the present study, the tanks were charged at about 200 psi before starting the

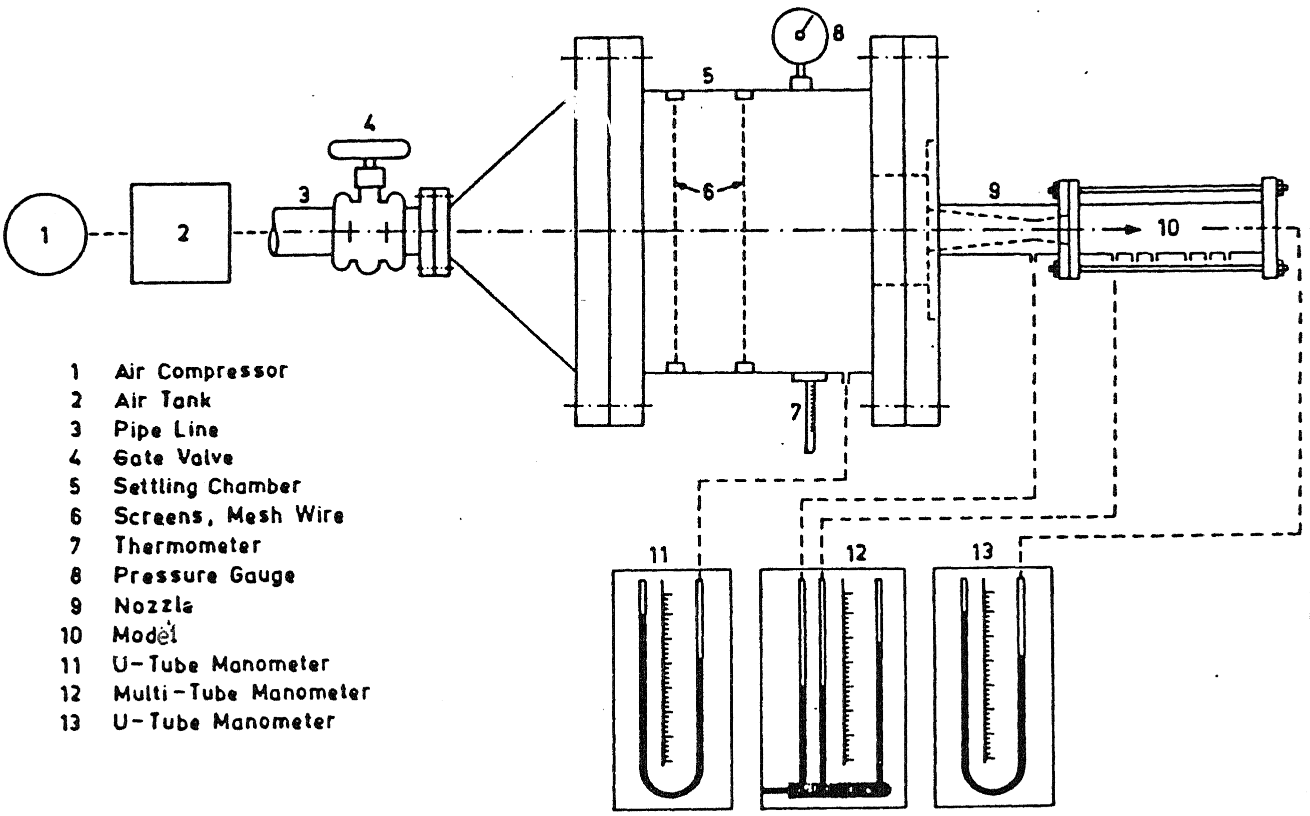


Figure 1: Schematic diagram of experimental set-up

experiments.

3.2 Flow System

The flow system consists of the pipe lines, pressure regulating valves and the settling chamber. The compressed dry air at high pressure is allowed though a gate valve and a pressure regulating valve, before reaching the settling chamber. The air is brought to stagnation in the settling chamber, before expansion through the experimental models. The settling chamber is provided with a diffuser followed by wire mesh screens to achieve stagnation isentropically. The settling chamber was fabricated out of a mild steel cylinder having inner diameter of 406 mm, length 546 mm and wall thickness 6 mm. A pressure lead was connected to U-tube manometer to measure the settling chamber pressure. It was also read by a dial gauge.

The level of stagnation pressure in the settling chamber is controlled by the pressure regulating valve, from few mm of mercury to few atmospheres, and the pressures required for the present studies have been achieved with this valve. The dry air at a settled equilibrium at a desired pressure was expanded through the experimental model which is a nozzle followed by a suddenly enlarged duct. The flow of air coming out from the enlarged duct was discharged to the ambient atmosphere. The entire flow system was tasted up to a pressure of 500 psi.

3.3 The Experimental Models

The models of the present study consist of an axisymmetric nozzle followed by a concentric axisymmetric duct of larger cross-sectional area. For nozzle exit Mach numbers in the range from incompressible subsonic to unity, a conical convergent

nozzle, shown in Fig. 2 was used. The exit diameter 10 mm of the nozzle was

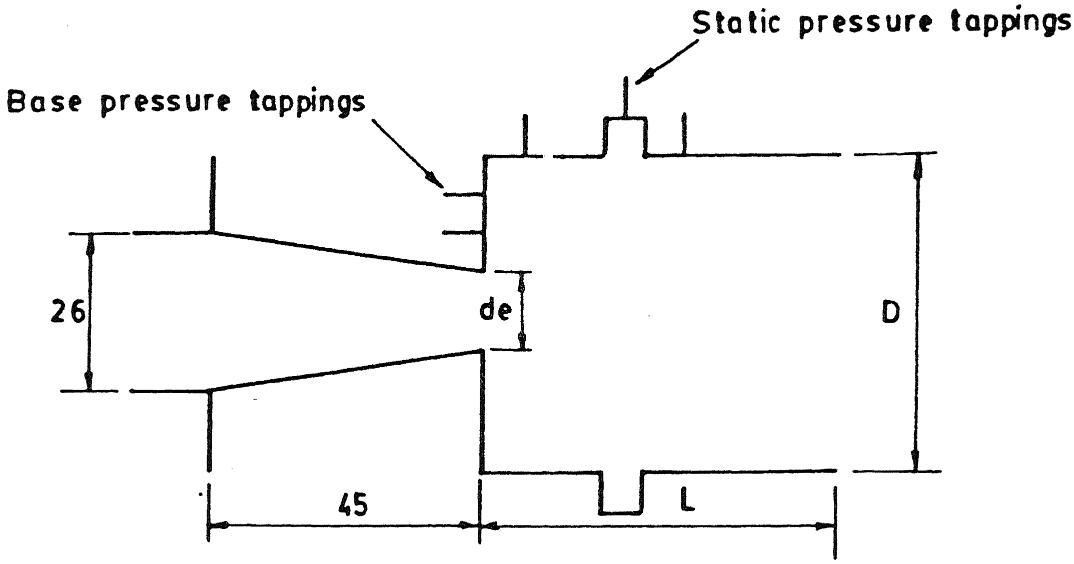
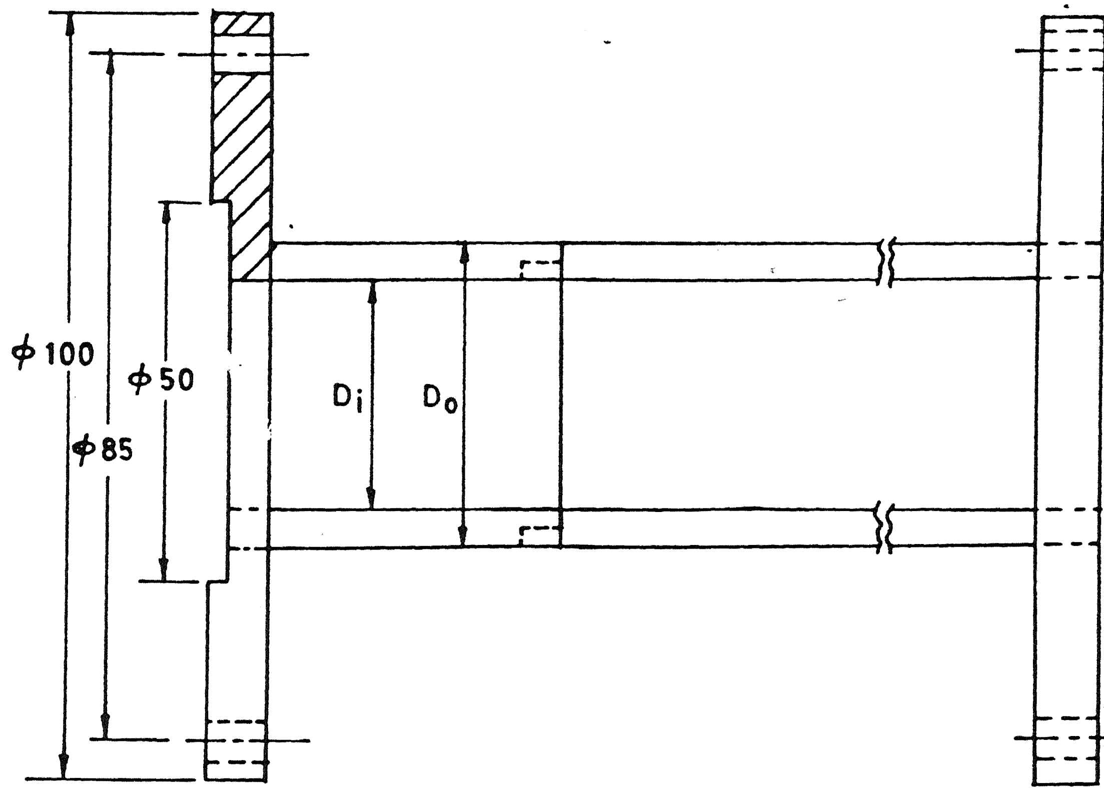
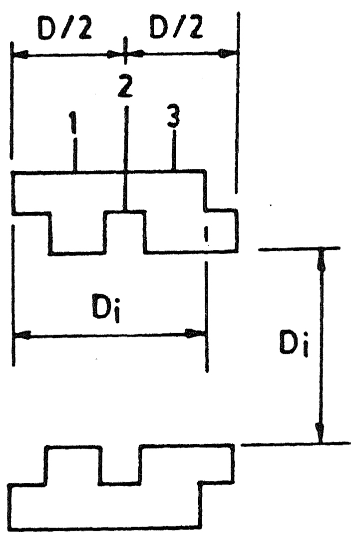


Figure 2: Sudden expansion model with convergent nozzle

kept constant and different area ratio of the model, defined as the ratio of the cross-sectional area of the enlarged duct to that of the nozzle exit, was achieved by changing the diameter of the enlarged duct. For every diameter of the enlarged duct, its length-to-diameter ratio was varied from 1 to 10 by adding pieces of one diameter length each and holding them together with a flange and threaded rod arrangement, shown in Fig 3. Care was taken to ensure that there were no leaks at the joints during the experimental runs.

The supersonic nozzles used were convergent-divergent type, as shown in Fig. 4. The exit diameter of these nozzles were kept the same as that of convergent model in order to maintain the area ratios same for both convergent and supersonic nozzles, with the same set of enlarged ducts. The required supersonic Mach numbers were achieved by adjusting the throat diameter of the nozzles to result in the appropriate





Specefication of model

Sl.no.	D_i	D_o	Ar
1.	31.6	43.6	10.00
2.	24.5	36.5	6.00
3.	17	29.0	2.89

1, 2 & 3 Static probes

$L = D_i$

Figure 3: Details of enlarged duct and schematic of model

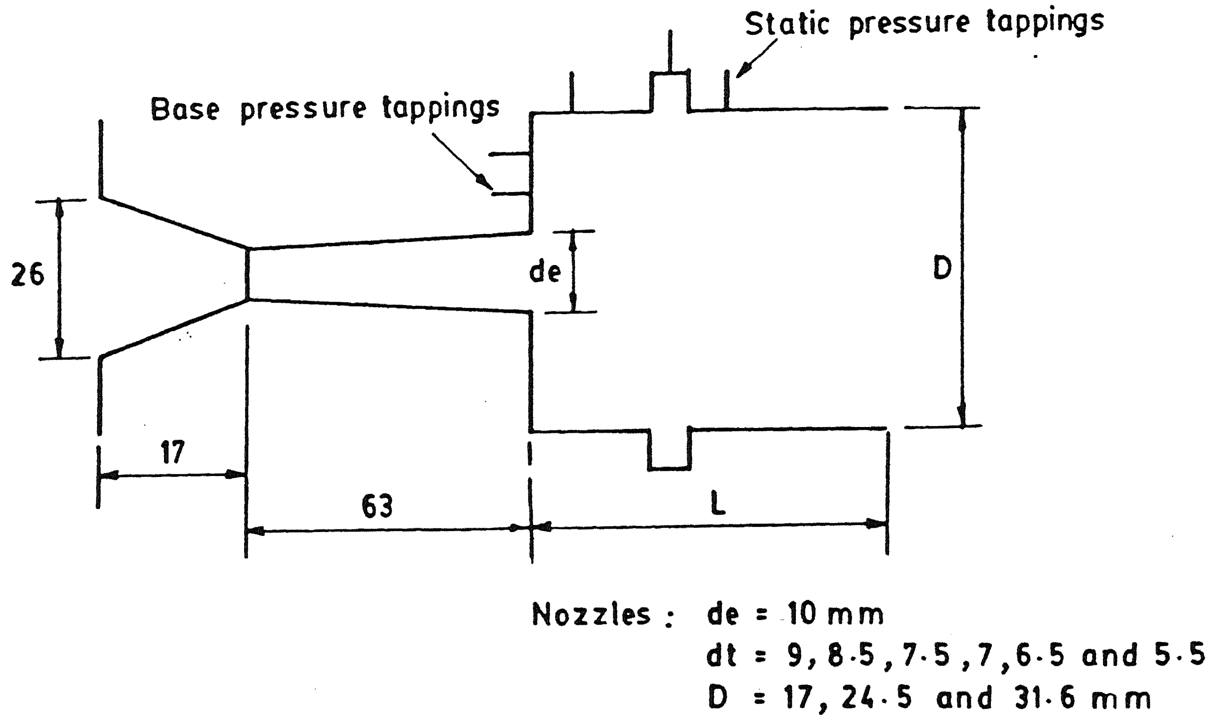


Figure 4: Sudden expansion models with convergent–divergent nozzle

area ratios required for the supersonic Mach numbers of interest. The nozzles to give Mach number range from 0.60 to 2.75 were fabricated out of extruded brass rod and tested. A total of seven nozzles were fabricated for the present study. Among the seven nozzles three were parallel nozzles fabricated using method of characteristic contours for comparison of the suddenly enlarged flow fields from conical and parallel nozzles.

3.3.1 The Nozzle Details

Six convergent-divergent nozzles were fabricated with the same exit diameter 10*mm* and the throat diameters were 9.0, 8.5, 7.5, 7.0, 6.5, and 5.5 *mm* and the corresponding Mach numbers were 1.58, 1.74, 2.06, 2.23, 2.40, and 2.75 respectively. Every nozzle was given convergence angle of 30°. The diffuser angle was kept at 10° for the three nozzles with throat 9.0, 7.5, and 6.5 *mm* for convergent-divergent

Table 1: Specifications of the nozzles

S.No.	Desig.	Throat dia. (mm)	Length (mm)	A/A_*	Mach No –
1	N_1	10.0	45.0	1.0000	1.00
2	N_2	9.0	30.0	1.2346	1.58
3	N_{2l}	8.5	53.0	1.3841	1.74
4	N_3	7.5	37.0	1.7778	2.06
5	N_{3l}	7.0	63.0	2.0408	2.23
6	N_4	6.5	47.0	2.3669	2.40
7	N_{5l}	5.5	64.0	3.3058	2.75

conical nozzles. The remaining three nozzles with throat diameter 8.5, 7.0, and 5.5 *mm* were fabricated with method of characteristics (MOC) contours with the help of the available form tools. The nozzles with MOC contours had larger length after the throat compared to convergent-divergent conical nozzles. For subsonic and sonic Mach numbers one convergent nozzle with 10.0 *mm* exit was also fabricated.

3.3.2 Designation of the Nozzles

The specifications of the nozzles used in the experiments are given in Table 1.

The nozzles designated as N_2 and N_{2l} had nominal throat diameter almost the same but N_{2l} has length after the throat due to MOC contour. Similar was the case with the nozzles N_3 and N_{3l}. Nozzle N_{5l} also had MOC contour after the throat.

To measure the base pressure two tappings were taken at the radial positions of 6.5 and 7.5 mm from the axis of the duct.

3.4 Suddenly Expanded Ducts

The suddenly expanded ducts were fabricated out of brass. Three sets of models were fabricated with area ratios 10.00, 6.00 and 2.89. Each model contained ten pieces of length to diameter ratio 1 so that the complete set can have L/D ratio varying from 1 to 10. The area ratio for the model was defined as the ratio of the enlarged pipe area to that of the nozzle unit. The ratios used were 10.00, 6.00 and 2.89. The pressure tappings were made with 1.6 m OD stainless steel tubes inserted into the models, as shown in Fig. 5, and Fig. 6 and these tubes were made airtight

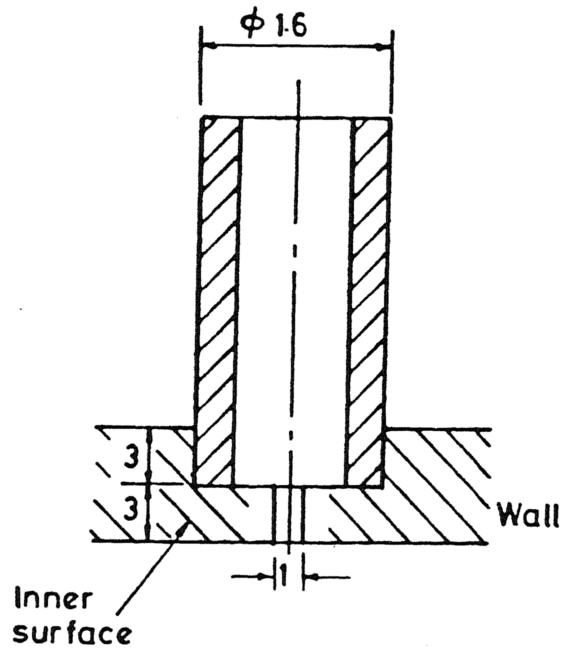


Figure 5: Details of wall pressure tappings

with help of Araldite. After experimentation with straight models without annular cavities, cavities were provided on each model at fixed intervals as was shown in Fig. 2. The cavity had width and depth of 3 mm each and later on for further experimentation the width was increased to 6 mm keeping the depth same. The aspect ratio of the cavity was defined as the ratio of width to depth. The static

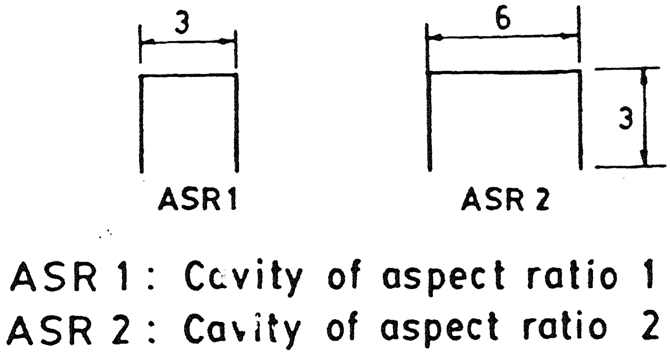


Figure 6: Details of cavity

pressure tappings at equal intervals were provideed on each model along its length. The distances between tappings were kept 3,5, and 8 mm for the models of area ratios 2.89, 6, and 10 respectively. The details of the tappings are shown in Fig. 5 and Fig. 6.

3.5 Measuring Instruments

The following measuring instruments were used:

1. A long 'U' tube mercury manometer was fabricated to measure settling chamber pressure P_{01} in conjunction with a dial gauge.

2. Another 'U' mercury manometer was fabricated to measure the total pressure at the exit of the enlarged duct. The total pressure at the exit was measured with help of a total pitot probe, made of stainless steel tube of 1.6 mm outer diameter.

3. A mercury multimanometer was fabricated for measuring base pressure and the wall pressures at various X/L locations.

4. A thermometer was provided to measure the settling chamber temperature.

5. A mercury barometer was used to measure the ambient pressure.

3.6 Experimental Runs

As shown in Fig. 1 compressed air for the storage reservoir was allowed through a gate valve to settling chamber ahead of the nozzle section. The settling chamber was utilized to allow the air to enter the nozzle at very low velocities. Stagnation pressure in the settling chamber was controlled by the pressure regulating valve and it was varied from 2.10 atmosphere to 3.48 atmospheres.

The behaviour of the flow in the enlargement was determined by the wall static pressure measurements as well as by the measurements of base pressure. Stagnation pressure ratio was varied from 2.10 to 3.48 in steps of 0.28. Area ratio was varied from 10.00 to 2.89. Cavity aspect ratio used were 1 and 2. For each area ratio, the L/D ratio used were 1,2,3,4,5,6,8, and 10. Three types of models were tested; first the models with straight inner surface, second the models with cavity aspect ratio 1 and third the models with cavity aspect ratio 2. The procedure adopted in the experiments were the same for every test run made. The first step in the experimental procedure was to charge the compressed air storage tanks. Then the stored dry air at high pressure in the tanks was allowed through the valves to flow through the experimental model. A view of the experimental model connected to stagnation chamber with base pressure and static pressure tapping connection are shown in Fig. 1.

The flow was adjusted with the regulating valve unit. The desired pressure at the stagnation chamber was reached and maintained. When the flow became steady

the primary pressure at the stagnation chamber was recorded. At the steady flow conditions, the base pressure, the wall static pressures and the total pressure at the unit were noted from the manometers. The total pressure at the stagnation chamber and the total pressure at the unit were measured with the long column 'U' tube mercury manometers.

When data for all the primary pressure ratios starting from 3.48 to 2.10 in the steps of 0.28 had been obtained for a particular L/D ratio of the enlarged duct, the L/D ratio was changed to get another desired L/D ratio. then again starting with a primary pressure ratio of 3.48, the entire process was repeated. Then the model was provided with cavity of aspect ratio 1 and the whole process was repeated. Then the same model was provided with cavity of aspect ratio 2 and the same process repeated. Thus the readings for one area ratio were taken.

Upon completion of tests for one area ratio the enlargement duct was removed and the next duct was fitted to the nozzle and the data for new area ratio was obtained by repeating the entire process.

3.7 Data Analysis Procedure

The base pressure and the wall static pressure were non-dimensionalised with the ambit pressure as P_b/P_a and P_w/P_a, respectively, after recalculating all readings from gauge pressure to absolute pressures. Total pressure loss was calculated in percentage by measuring the total pressure P_{01} in settling chamber and the total pressure P_{02} at the enlarged duct exit.

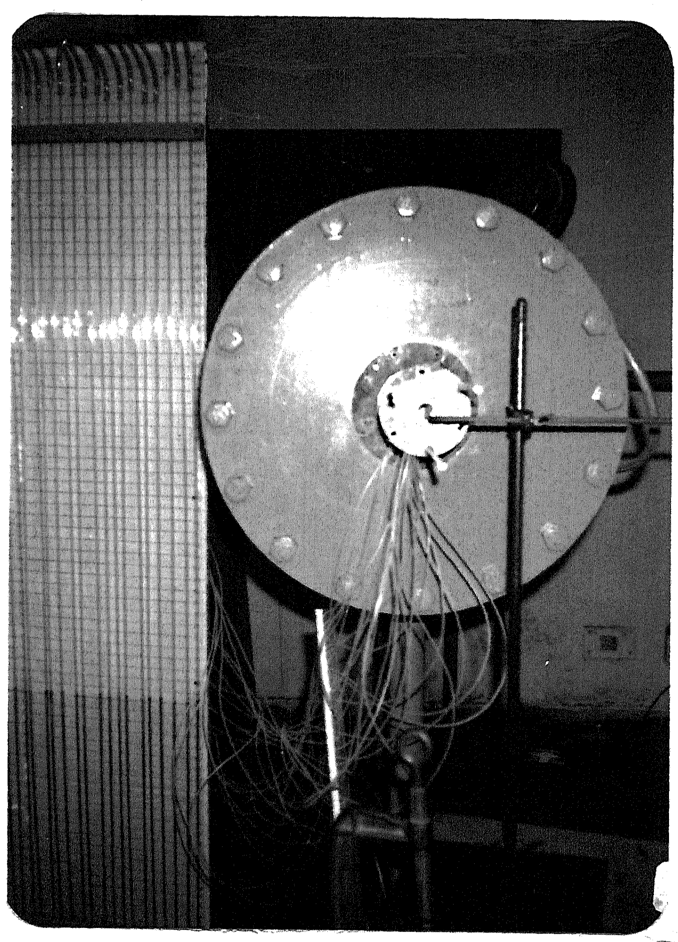


Figure 7: A view of the experimental set–up with model and instrumentation

Figure 8: Experimental model with wall pressure tappings and total pressure probe

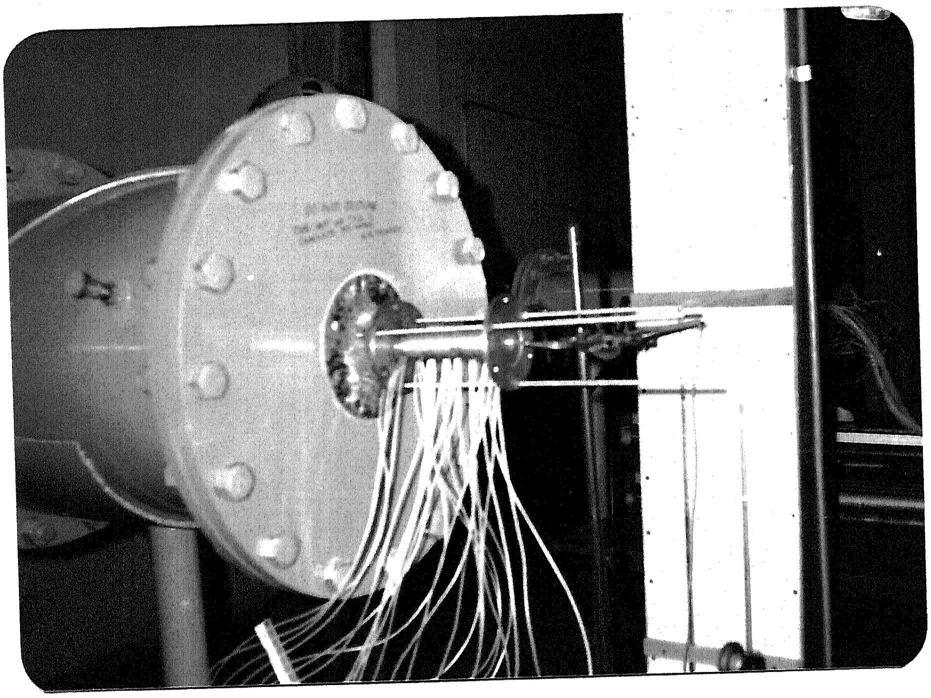


Figure 9: Experimental model with Pitot probe to measure pressure loss

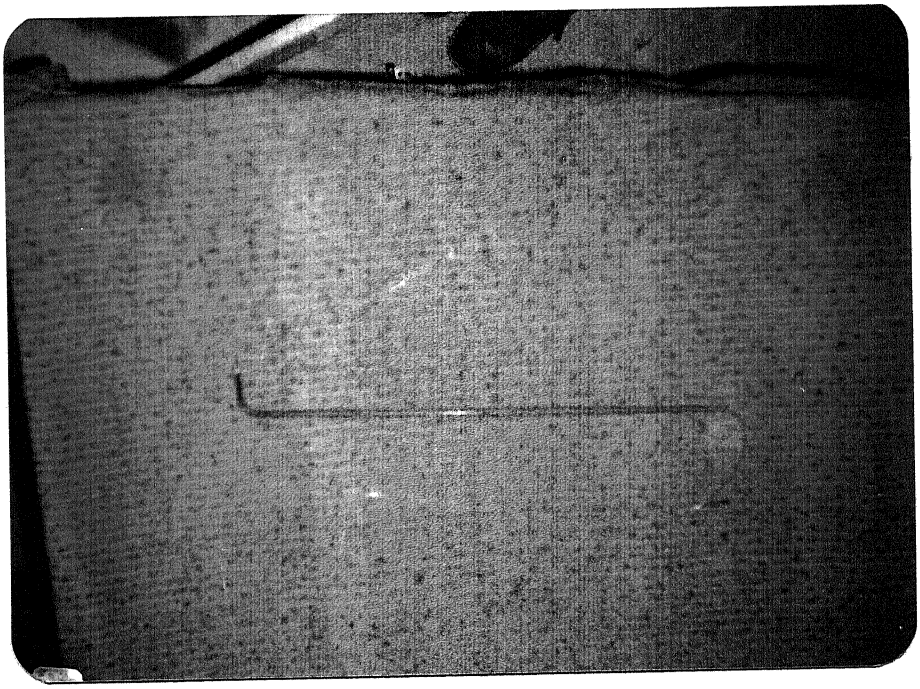


Figure 10: Pitot probe

Figure 11: A view of the nozzles used

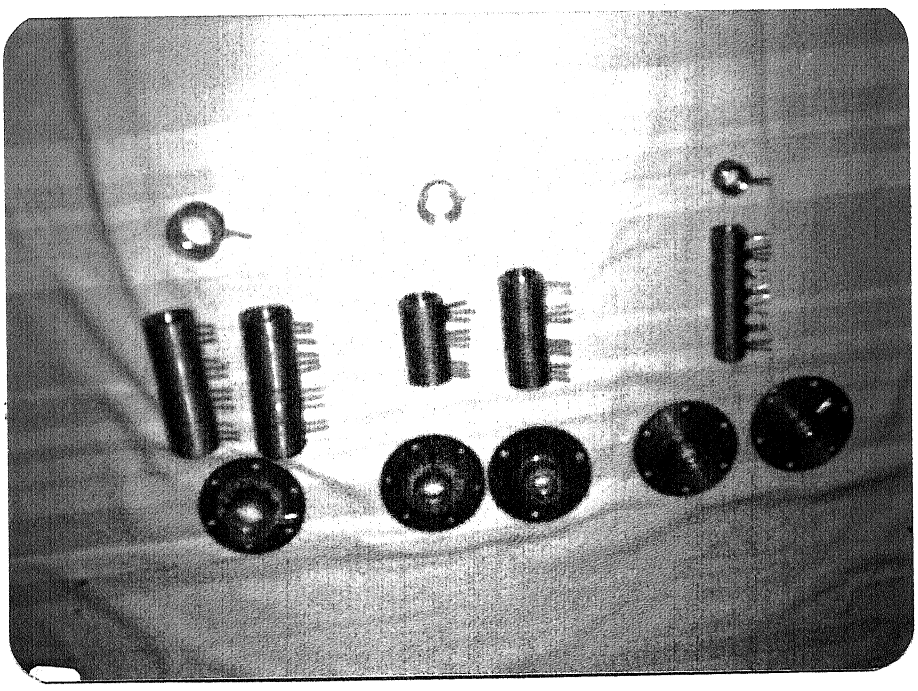


Figure 12: A view of the enlarged duct with flanges

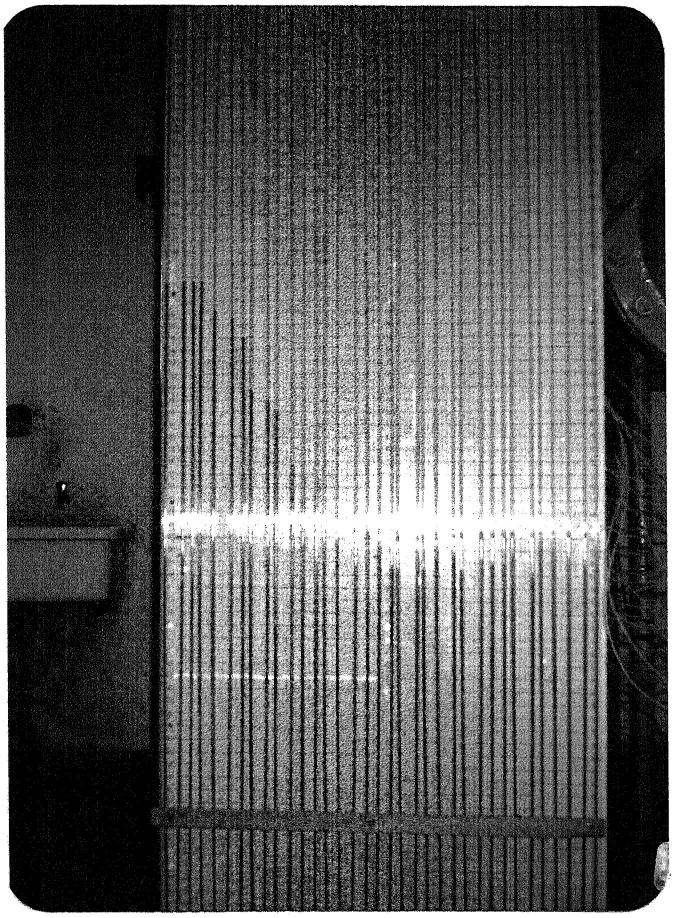


Figure 13: Multitube manometer

Chapter 4

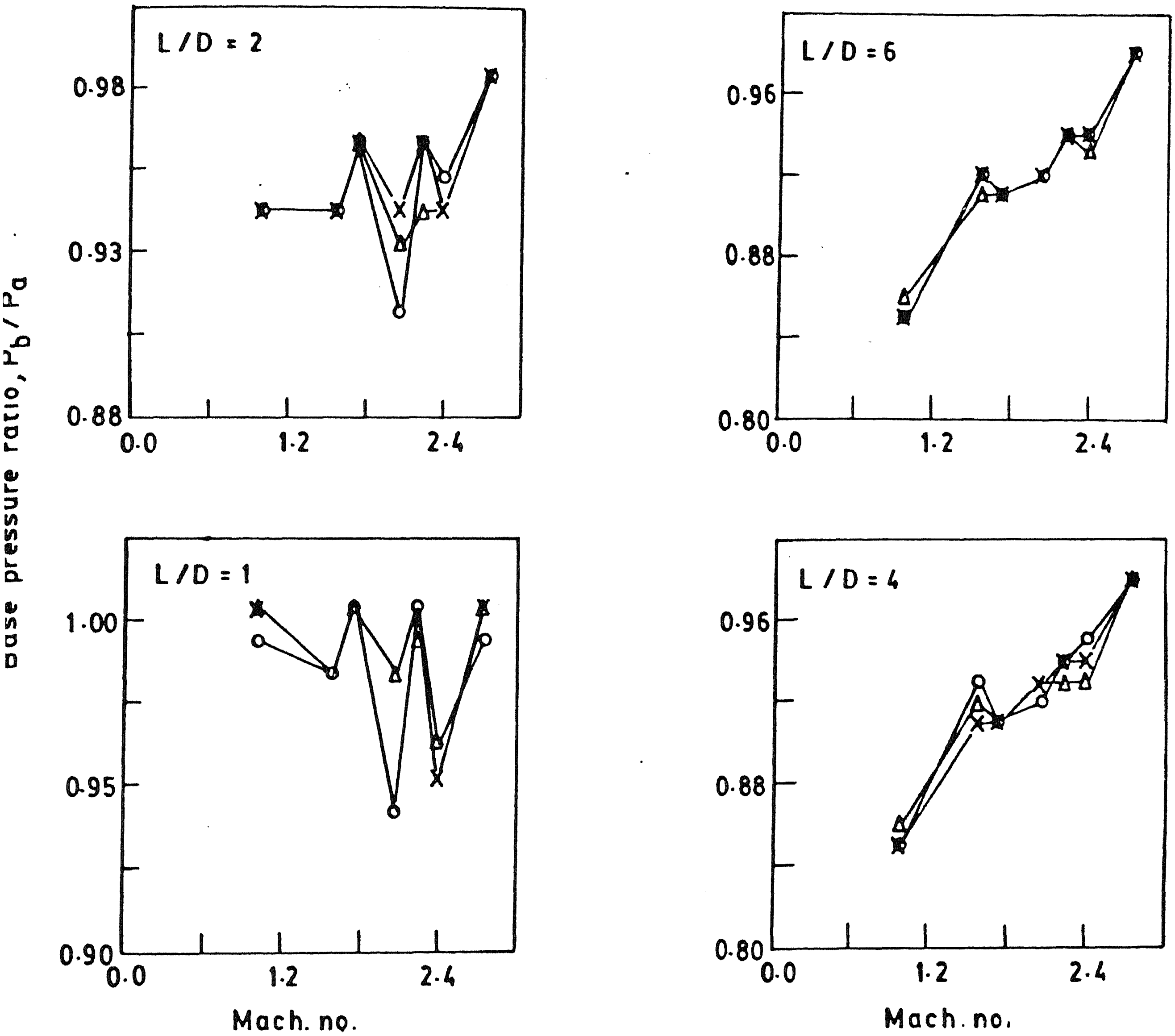
RESULTS AND DISCUSSION

4.1 Studies in Supersonic Regime

4.1.1 Variation of Base Pressure with Mach Number

The results of base pressure P_b/P_a of the present experimental investigation as a function of the parameters of nozzle exit Mach number, enlargement L/D ratio, model area ratio, primary pressure ratio P_{01}/P_a and cavity aspect ratio, defined as width to depth of the annular cavity, are presented in figures 14 to 22. Both base pressure and the primary pressure are non-dimensionalized with the ambient atmospheric pressure. Even though six primary pressures in the range from 2.10 to 3.48 have been tested, only three of them which are representative of the set are used for highlighting the base pressure and flow characteristics.

Figures 14 to 16 present base pressure variation with Mach number for area ratio 10 and primary presure ratios of 2.10, 2.65 and 3.48. It is seen from these figures that the enlargement length to diameter ratio has significant effect over the base pressure when the Mach number is more than 1.8. However, for low values of L/D ratio from 1 to 2 the effect of Mach number on the base pressure is only marginal. Also the



$P_{01} / P_a = 2.10$, $Ar = 10.0$; —o— ASR 2 , —x— ASR 1 , —△— ST

Figure 14: Base pressure variation with Mach number

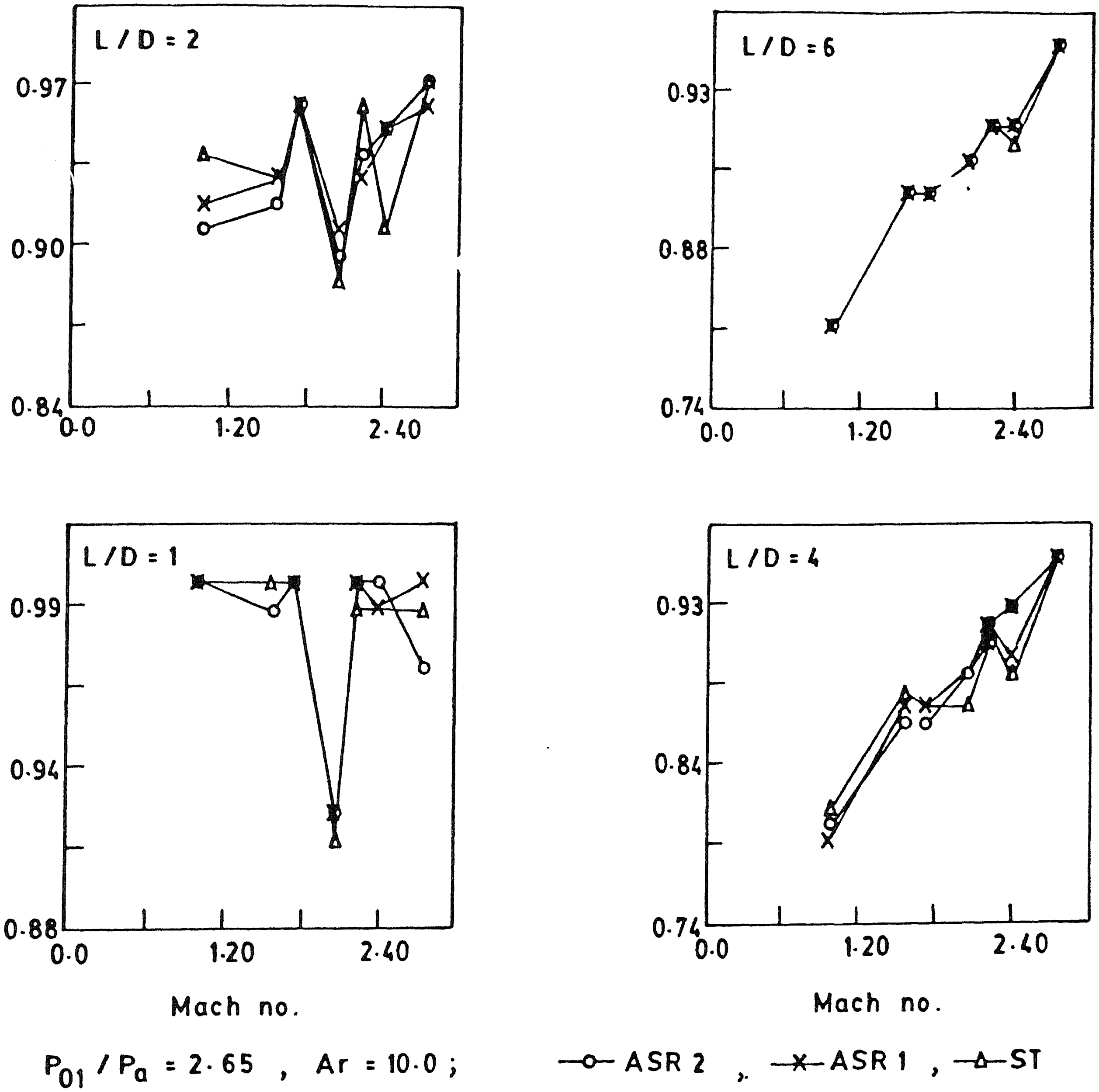


Figure 15: Base pressure variation with Mach number

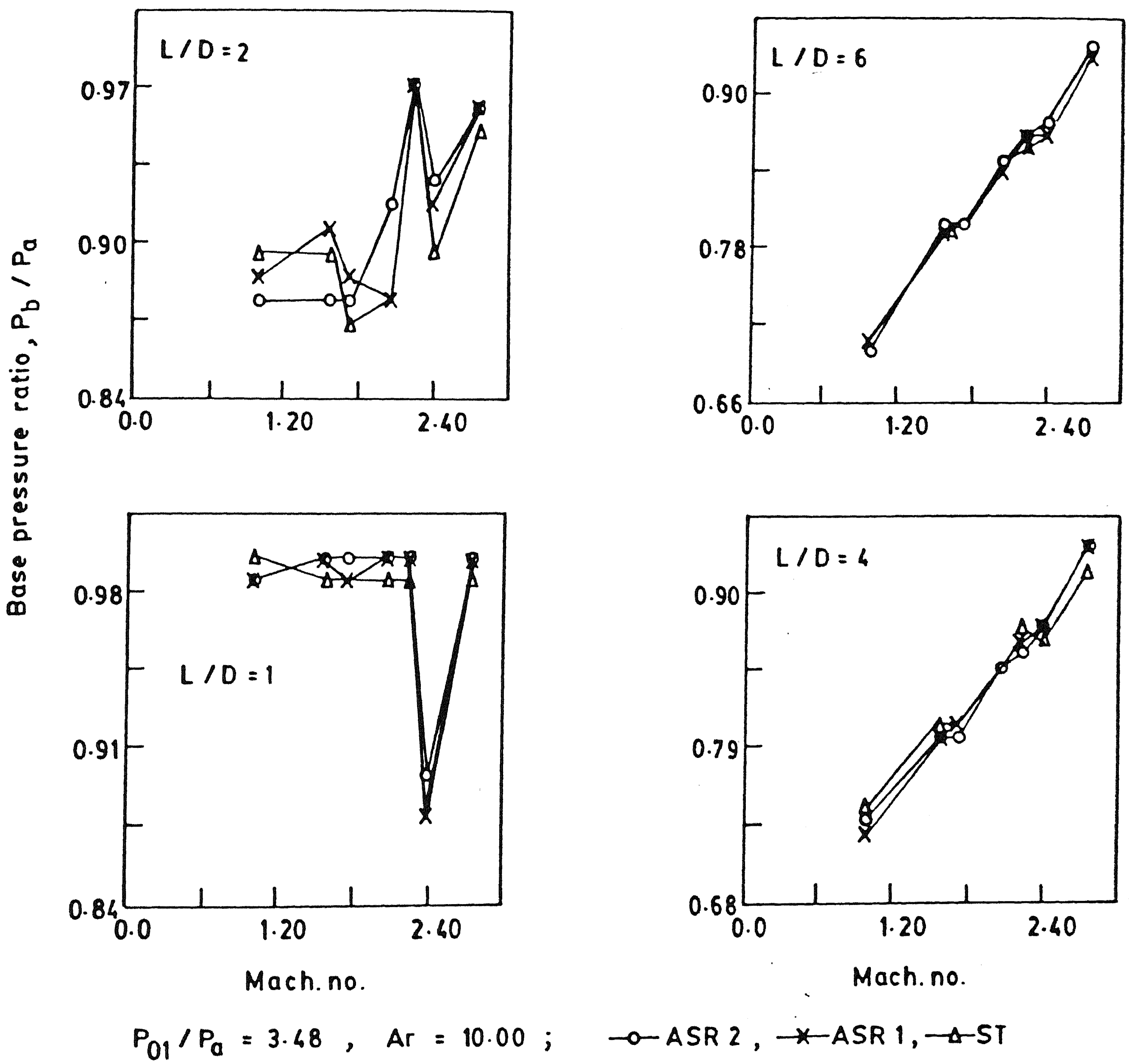


Figure 16: Base pressure variation with Mach number

variation of P_b/P_a with Mach number shows a steep increase with increasing Mach number for L/D 4 and 6. Whereas for L/D 1 and 2 the variation is not showing any specific trend. The reason for the above behavior of base pressure with Mach number may be attributed to the wave structure which is prevailing in the enlarged duct. Since the pressure ratio covered in the present study results in underexpanded flow as the nozzle exit for primary pressure ratio 3.48 for Mach number below 1.48 and for pressure ratios 2.65 and 2.10 the Mach numbers are 1.26 and 1.09 respectively. Thus for Mach number 1.2, the flow is under expanded for pressure ratios 3.48 and 2.65. Whereas the flow is overexpanded for pressure ratios 2.10. Therefore when the enlarged duct has sufficient length for the waves which are generated at the exit of the nozzle to attach, the under and over expansions control the base pressure. This aspect is clearly seen from the above figures. That is for L/D 4 and 6, it is seen from the figure that the underexpanded flow results in low base pressure at Mach 1.2 for longer ducts compared to the shorter ducts. This explains that the L/D 2 or less is not sufficient for the waves from the nozzle exit to attach with the duct. The random behavior of P_b/P_a with M also may be due to the fact that waves were unable to have any influence over the base pressure when the duct is very short.

For the nozzle exit Mach number more than 1.5 all the pressure ratios result in only over expansion, thereby generating shock at the nozzle exit. If the duct length is sufficient enough for this shock to attach, this will result in increase of pressure with increase in Mach number. This effect is clearly seen from these figures for L/D 4 and 6. The cavity aspect ratio has got only marginal effect on base pressure for L/D 6 and above at all the pressure ratios tested. However, for L/D less than six the aspect ratio has considerable influence on base pressure at all pressure ratios. But it does not show any well defined trend as it is seen form the figures 14 to 16.

The variation of base pressure with Mach number for model area ratio 6 is plotted

in figures 17 to 19 for other parameters same as in figures 14 to 16. It is clearly seen from these figures that the model area ratio has got very strong effect on the base pressure when the duct is of sufficient length for the flow from the nozzle to attach and propagate. Compared to area ratio 10, area ratio 6 results in significant reduction in base pressure for L/D 4 and 6. Further the cavity aspect ratio seems to have influence over base pressure even for L/D 4 and 6 unlike in the case of model with area ratio 10. For L/D 4 and 6 the increase in cavity aspect ratio results in decrease of base pressure at all Mach numbers even though the decrease is not high. However, for L/D less than 4 the effect of aspect ratio is not well defined as before.

The effect of decrease in model area ratio on the base pressure is seen from figures 20, 21 and 22 for primary pressure ratios 2.10, 2.65 and 3.48, respectively. The cavity influence on the base pressure is seen for all the Mach numbers tested even for L/D 4 and 6. However, for L/D 2 and 1 the behavior of base pressure with Mach number does not show any well defined pattern like that for the models with area ratio 6 and 10. But unlike the previous area ratios the base pressure increases with increasing Mach number even for L/D 2 and 1. This may be due to the fact that the enlargement area is small enough for the shocks/expansion waves to attach with the enlarged duct wall thereby influencing the base zone. That is increase in Mach number, resulting in increased degree of over expansion, generating stronger shocks at the nozzle exit forcing the base pressure to shoot up with Mach number increase is clearly seen from these figures.

4.1.2 Variation of Base Pressure with L/D Ratio

The cross plots of base pressure variation with L/D are shown in figures 23, 24 and 25. From these results it is evident that the effect of L/D on base pressure is drastic in the range of L/D from 1 to 6 for all the area ratio and at all primary pressure

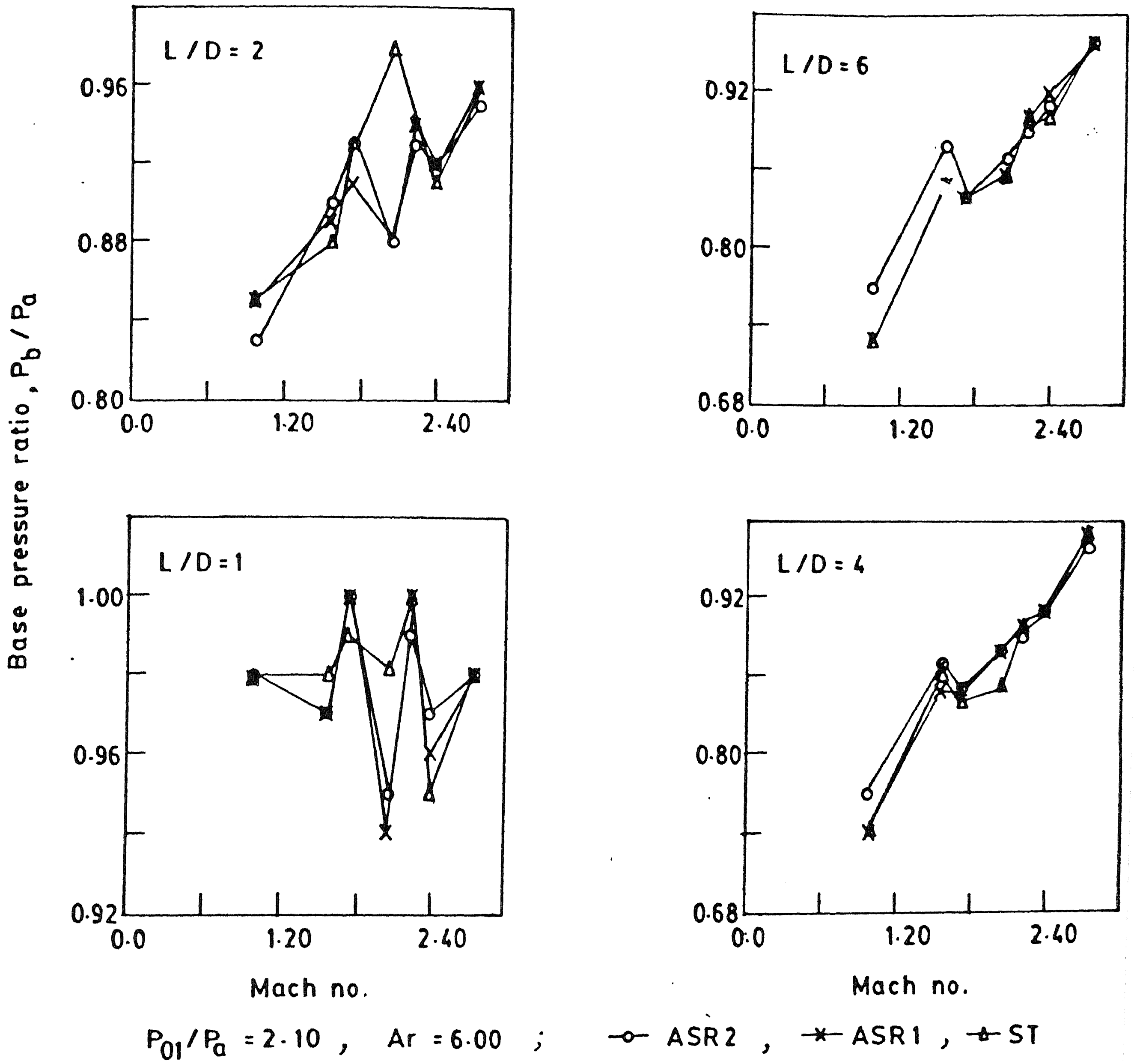


Figure 17: Base pressure variation with Mach number

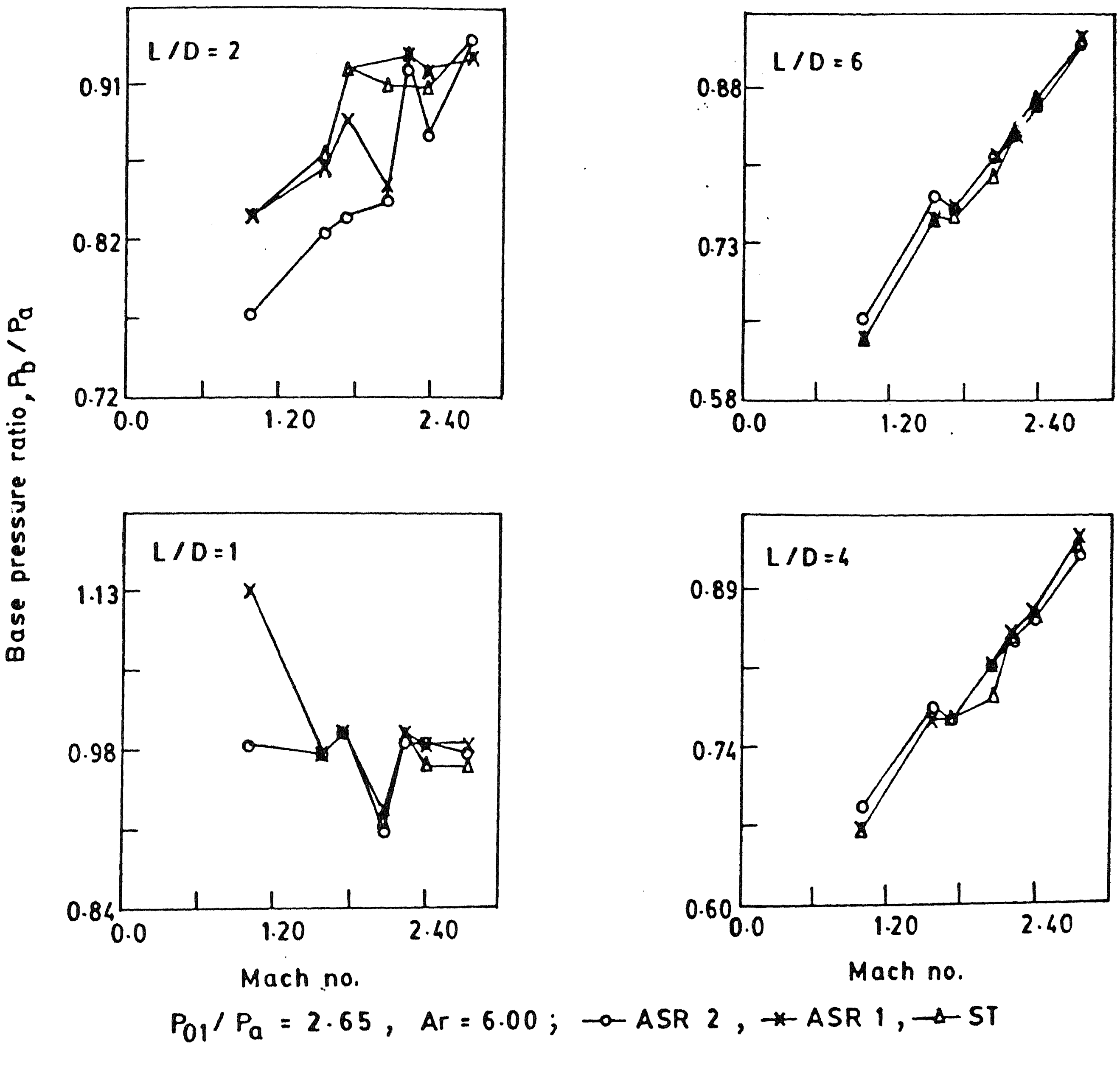


Figure 18: Base pressure variation with Mach number

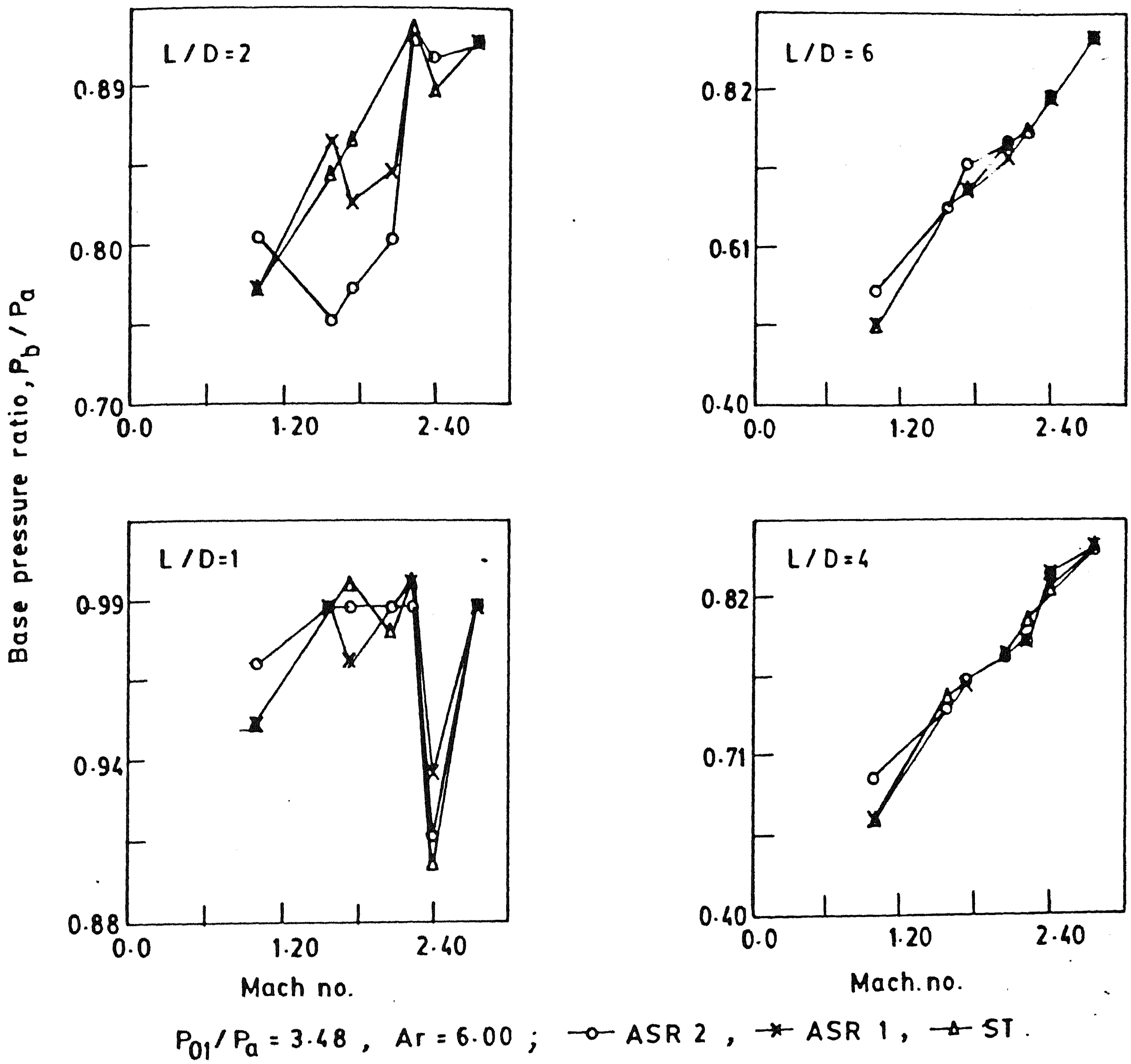


Figure 19: Base pressure variation with Mach number

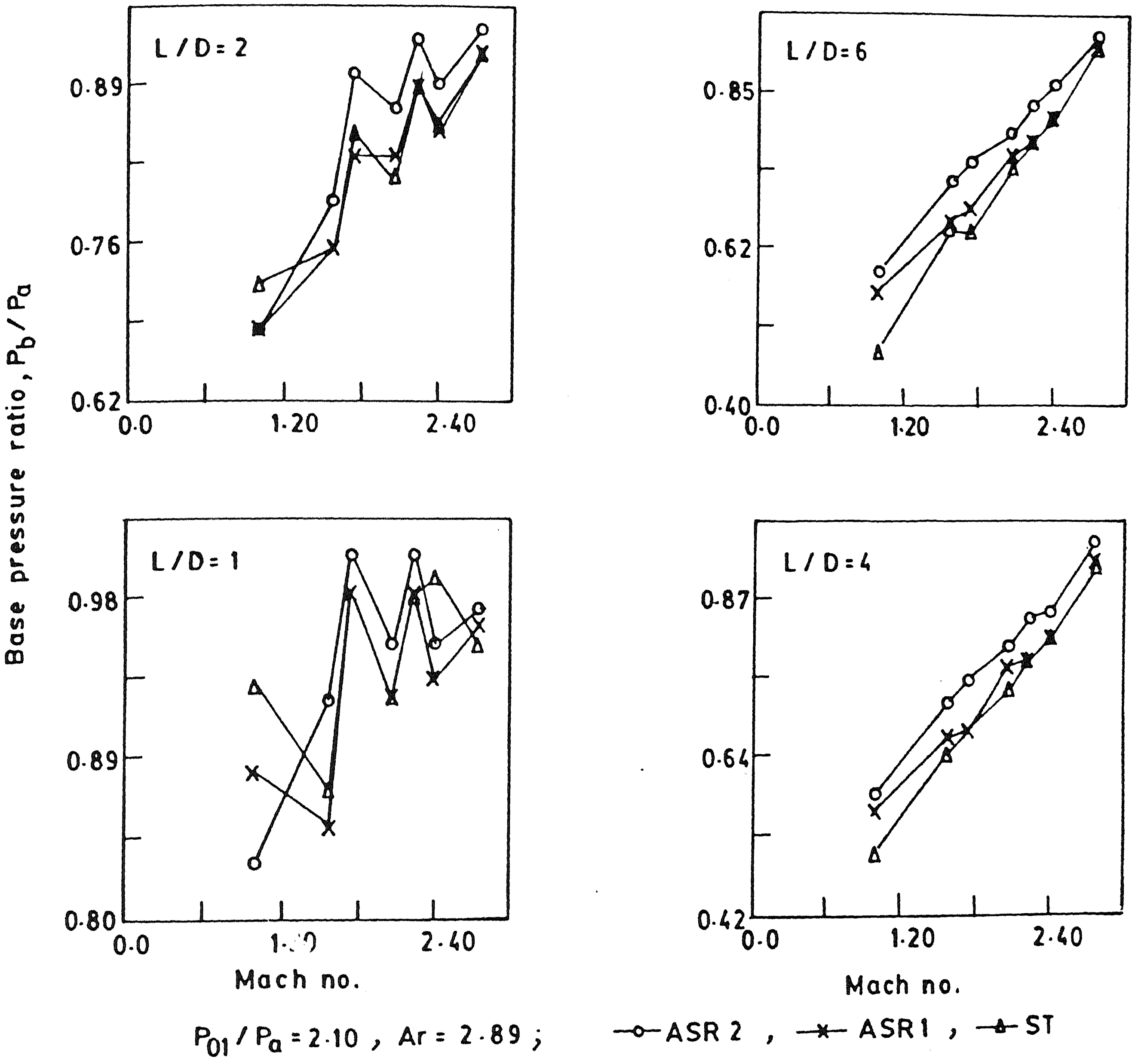


Figure 20: Base pressure variation with Mach number

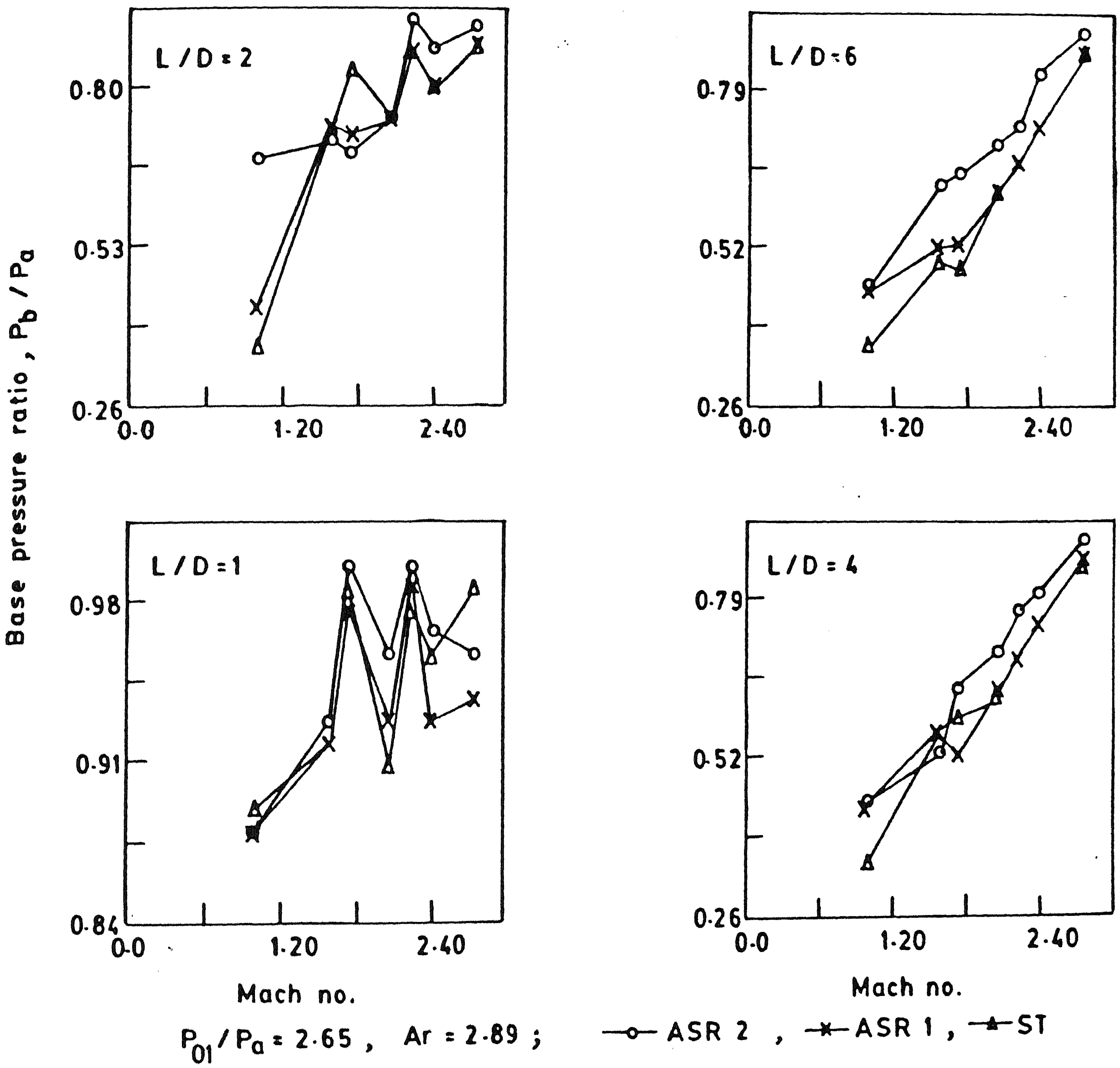


Figure 21: Base pressure variation with Mach number

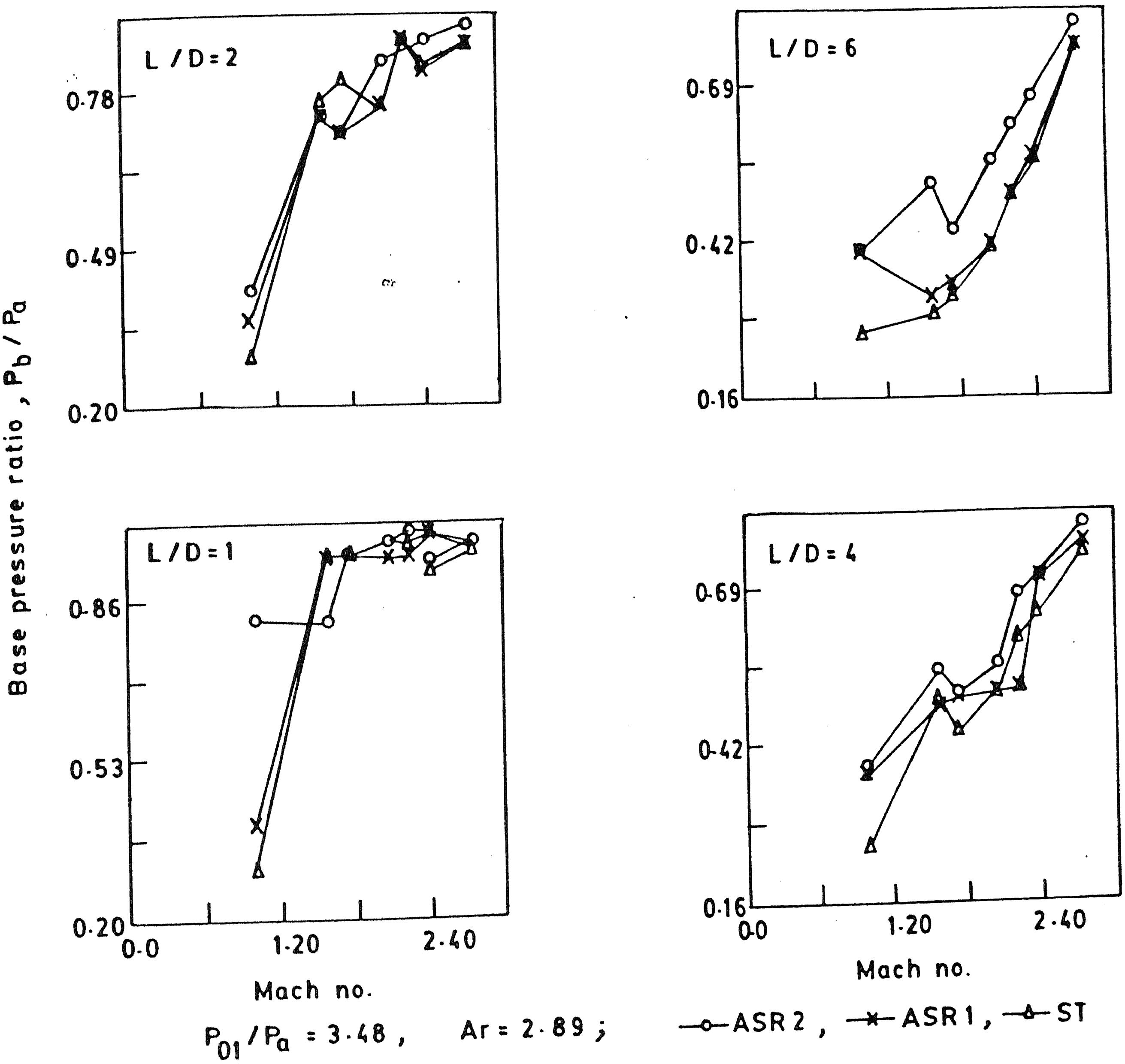


Figure 22: Base pressure variation with Mach number

ratios. For L/D more than 6 the base pressure becomes almost independent of L/D at all area ratios and primary pressure ratios. However, the cavity aspect ratio influences the base pressure for area ratio 2.89 significantly in the range of L/D from 6 to 10, making the base presure to assume values which are larger than that for models with plane wall. That is, the base pressure increases with increase in cavity aspect ratio for L/D more than 6. But for area ratio 6 and 10, as it was seen earlier that the secondary influence created by the cavity are unable to overcome the primary relief experienced by the main flow, thereby rendering the cavities to become ineffective in influencing the base pressure. This results of base pressure becoming independent of L/D, for L/D more than 6, is in excellent agreement with the results reported by Rathakrishnan and Sreekanta [34] with flow through tubes with smooth inner surface expanded suddenly into an axisymmetric tube of larger area.

4.1.3 Variation of Base Pressure with Primary Pressure Ratio

The cross plots of base pressure ratio P_b/P_a as a function of primary pressure ratio are presented in figures 26, 27 and 28 for model area ratios 10, 6 and 2.89 respectively. For area ratio 10, which is the geometry with maximum relief, in the present study, it is seen that the cavity aspect ratio seems to have practically insignificant effect on the base pressure when L/D is more than 4. Even for shorter ducts with L/D less than 3 the cavity influences is only marginal for pressure ratios upto 2.65. Only for higher pressure ratios there exists some marginal effect of the cavity on the base pressure. Even though the results presented are for the particular Mach number of 1.74, this is the trend for other values of supersonic Mach numbers tested. Further, when L/D is 1 for area ratios 10 and 6 the flow does not seem to influence

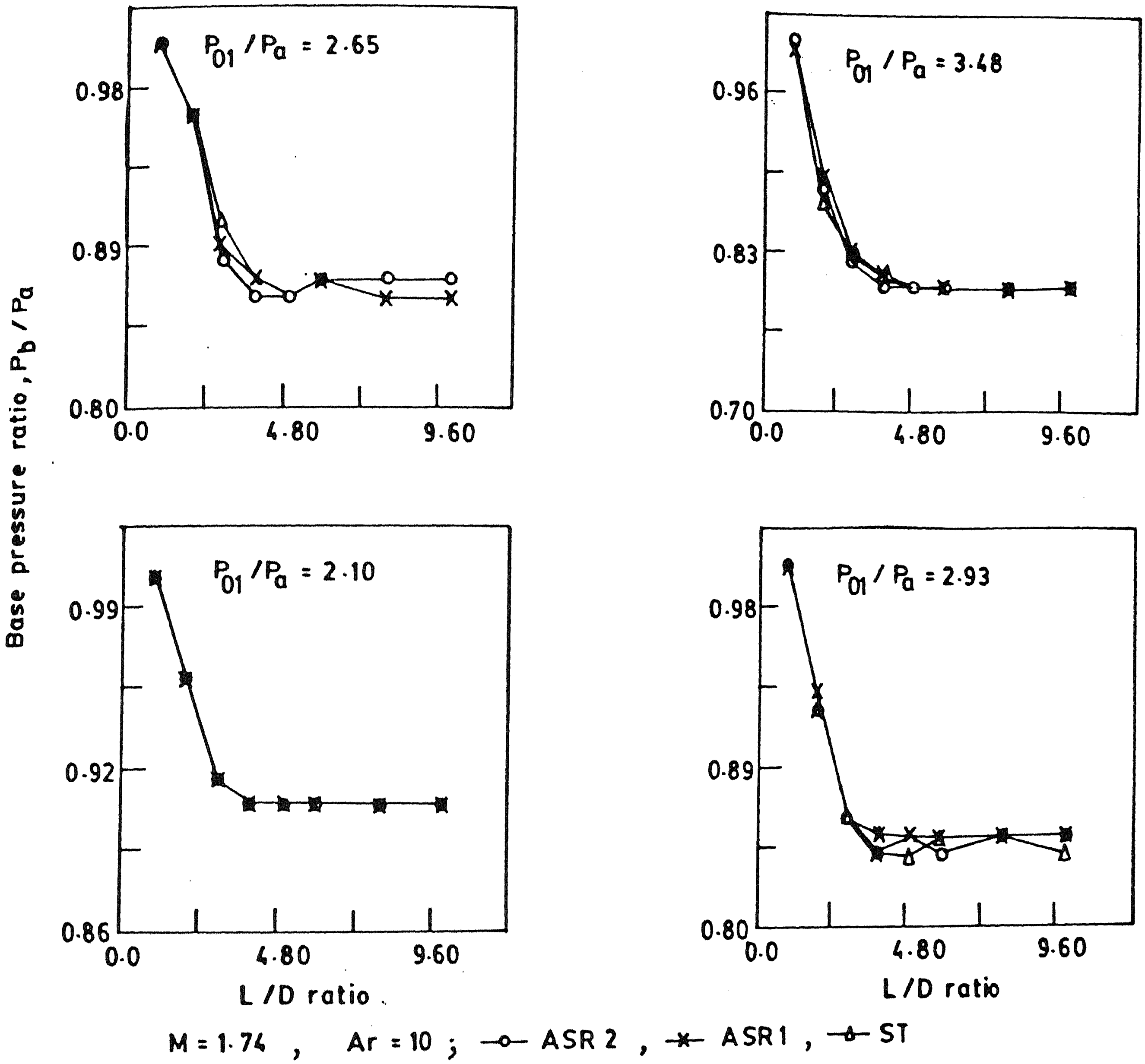


Figure 23: Base pressure variation with L/D ratio

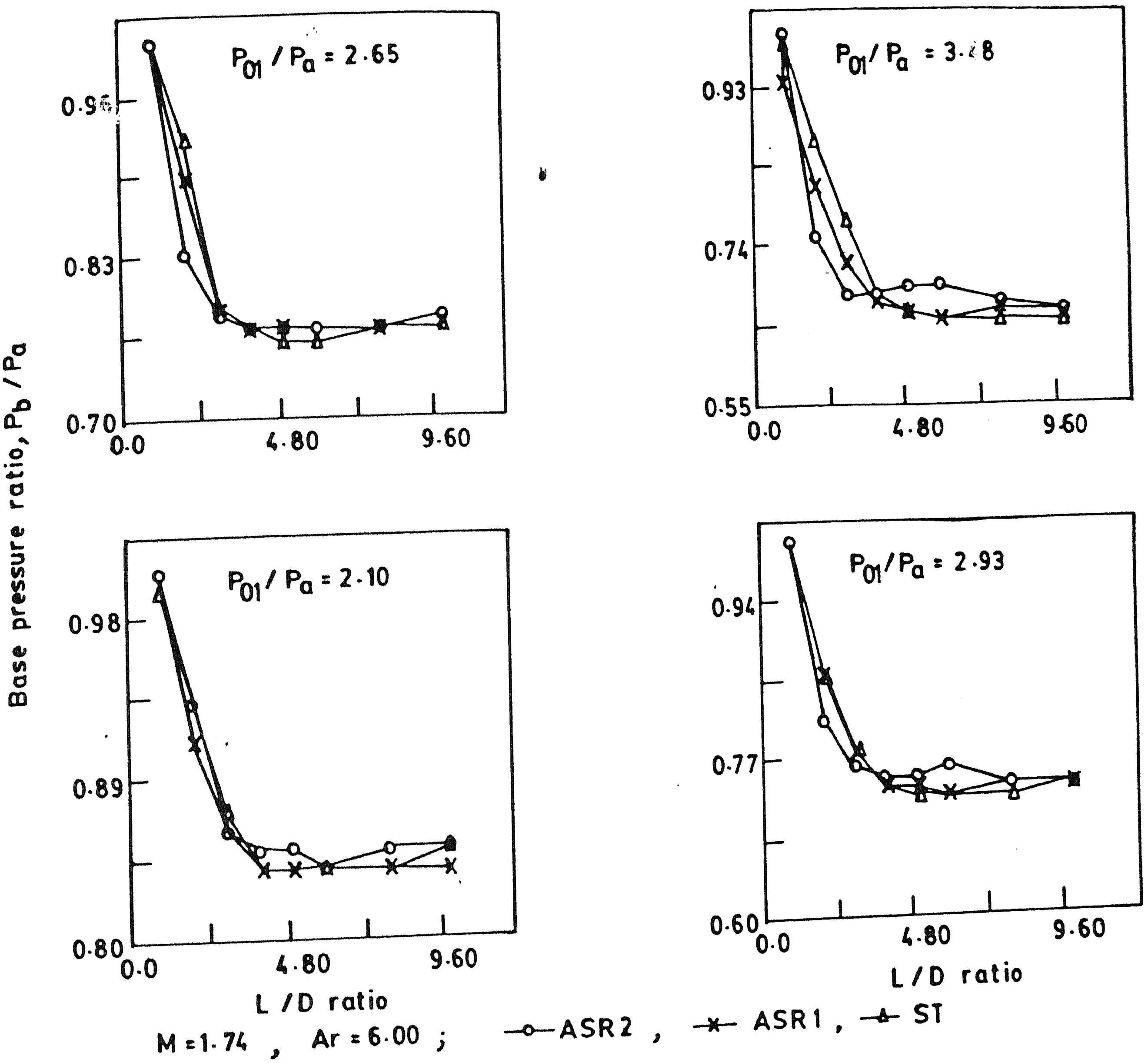


Figure 24: Base pressure variation with L/D ratio

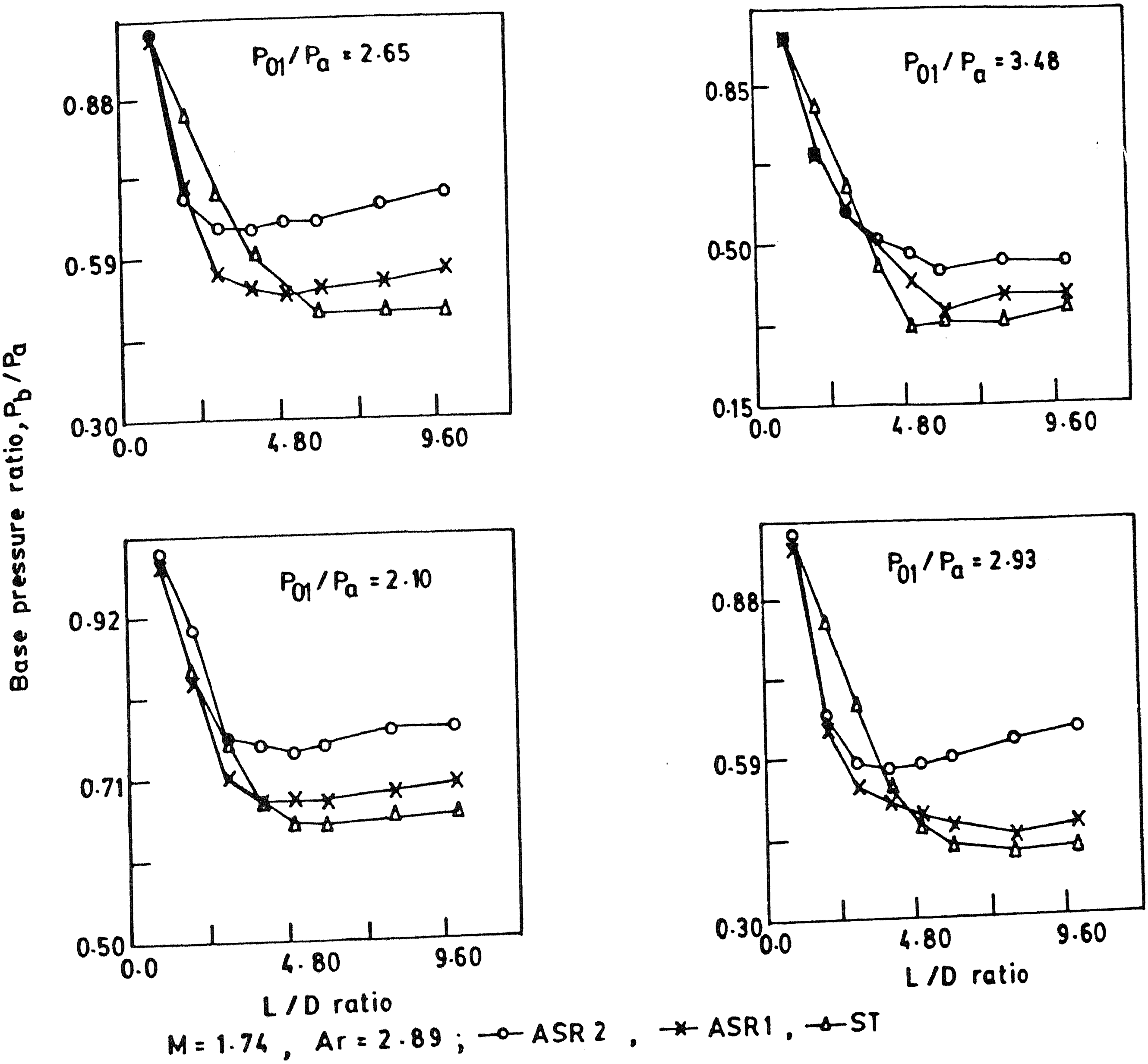


Figure 25: Base pressure variation with L/D ratio

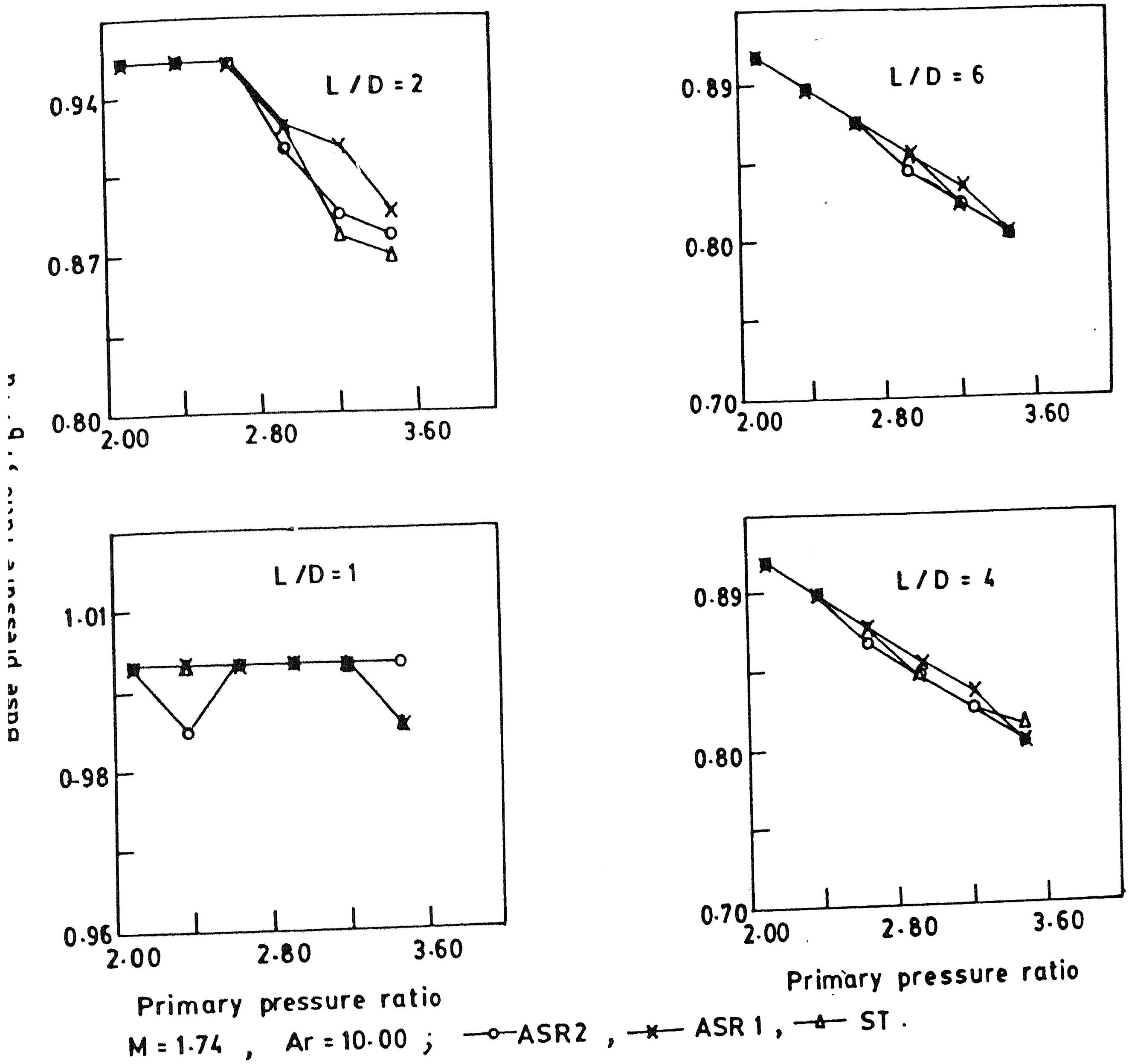


Figure 26: Base pressure variation with primary pressure ratio

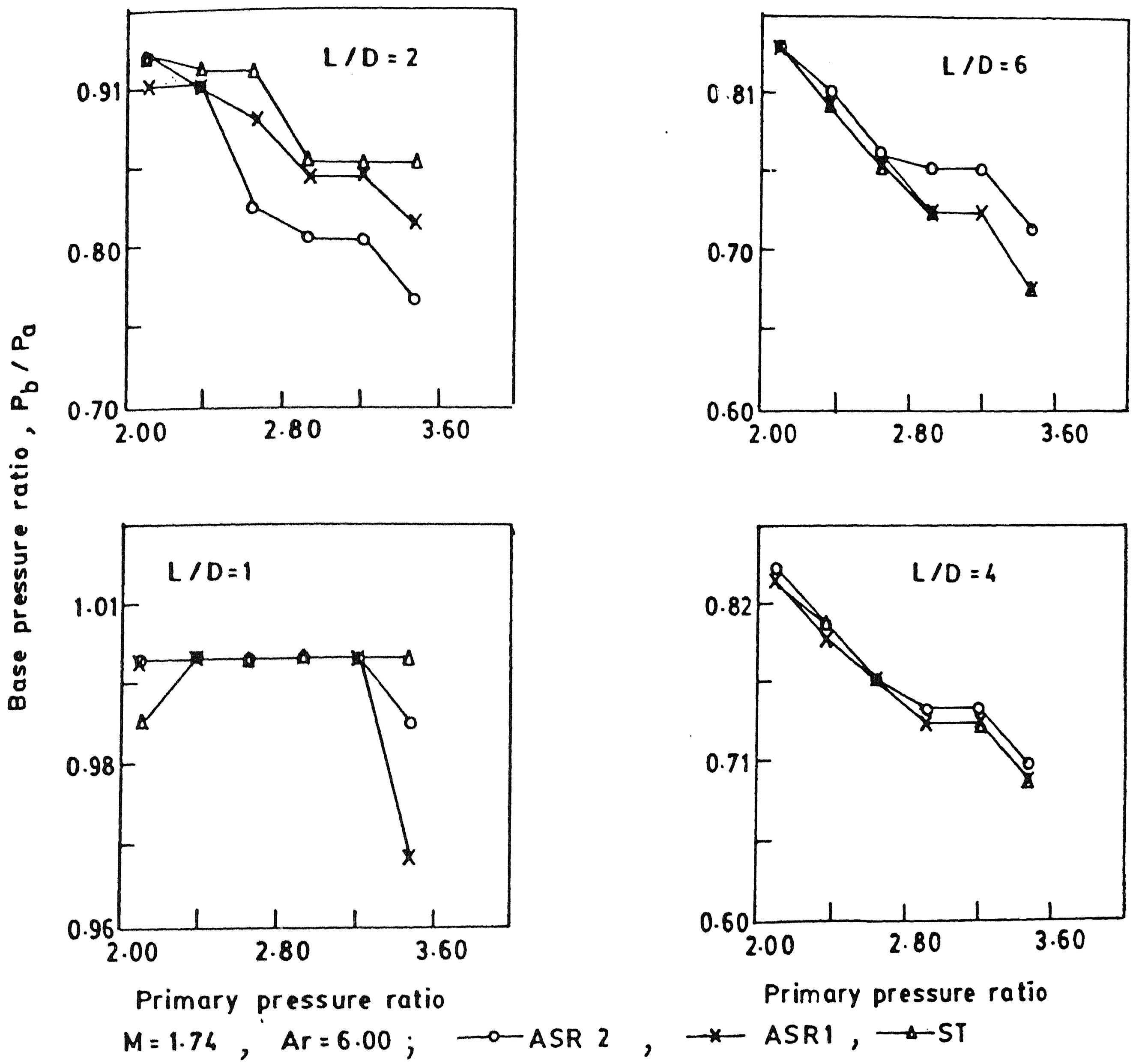


Figure 27: Base pressure variation with primary pressure ratio

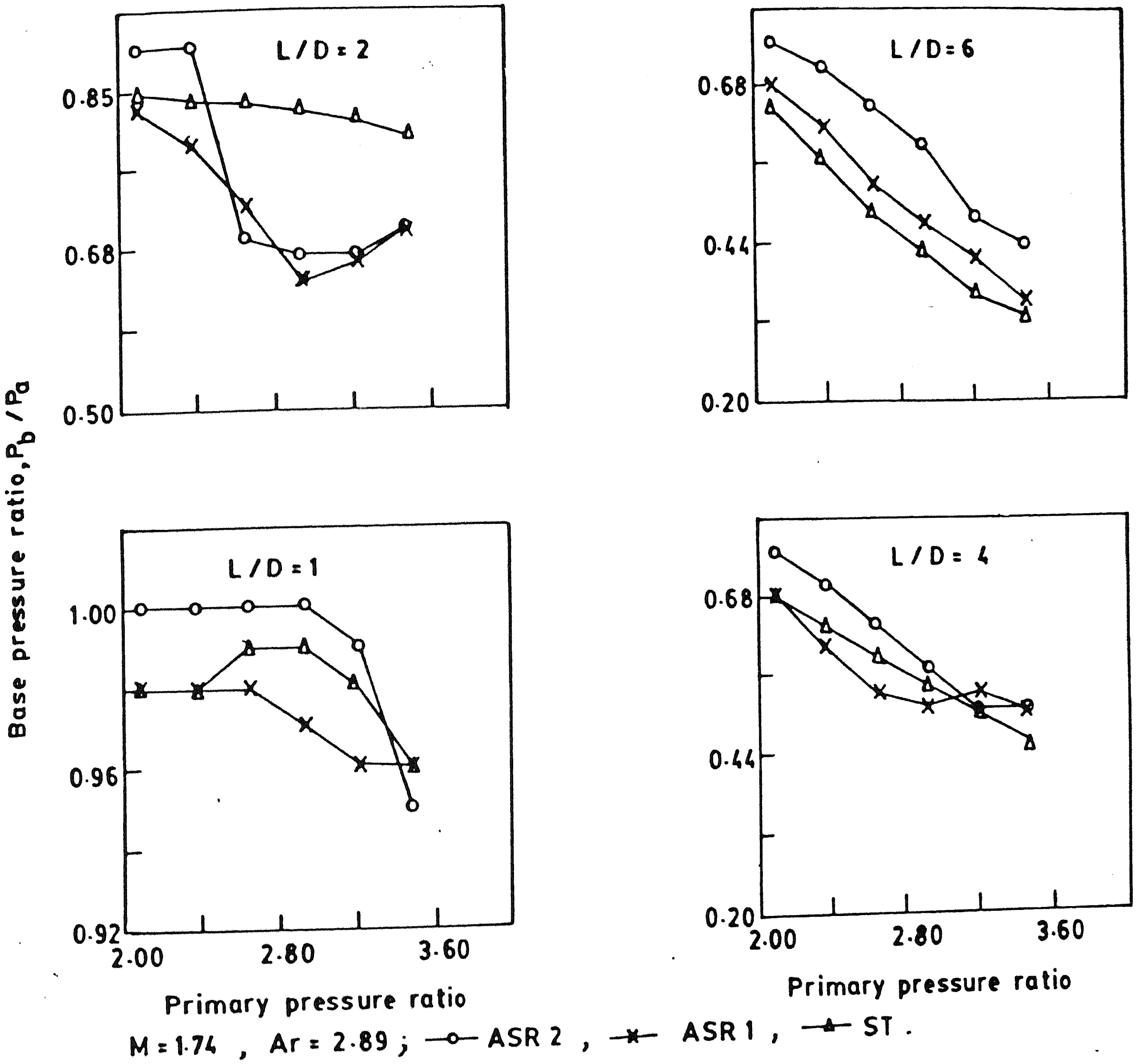


Figure 28: Base pressure variation with primary pressure ratio

the base region at all, thereby revealing that the enlarged duct length is not sufficient for the flow from the nozzle to get attached to the enlarged duct on expansion.

For area ratios 6, the cavity influences the base pressure significantly for L/D = 2. However, for L/D more than 4 the influence is almost nil upto pressure ratio of 2.93. For higher pressure ratios there is marginal effect of cavity on base pressure for aspect ratio 2.

The results for area ratio 2.89 shows that, the cavity has got significant effect at all values of primary pressure ratios and for all L/D values. This is due to the fact that the relief effect experienced by the flow at this area ratio is considerably less than that experienced by the flow for are ratios 6 and 10. Therefore the secondary disturbances introduced by the cavities could be able to influence the main flow field considerably, thereby rendering the base pressure to be a function of the cavity aspect ratio. Even at L/D = 1 the cavity influences the base flow indicating that, the flow from the nozzle could able to attach with the enlarged duct on expansion for this area ratio.

4.1.4 Variation of Base Pressure with Area Ratio

The results of base pressure variation with area ratio for Mach number 1.74 at three pressure ratios of 2.10, 2.65 and 3.48 are shown in figures 29, 30 and 31, respectively. It is seen from these figures that, for area ratio more than 6, the base pressure shows a monotonic increase with area ratio and it is independent of the cavity aspect ratio. For area ratio in the range from 2.89 to 6 the base pressure experiences very steep rise compared to its increase in the range of area ratio from 6 to 10. The aspect ratio influences the base pressure strongly for area ratio 2.89. However, the effect of area ratio on base pressure decreases with increase of area ratio. When the model is with L/D = 1, the behavior of base pressure with area ratio shows different behavior with

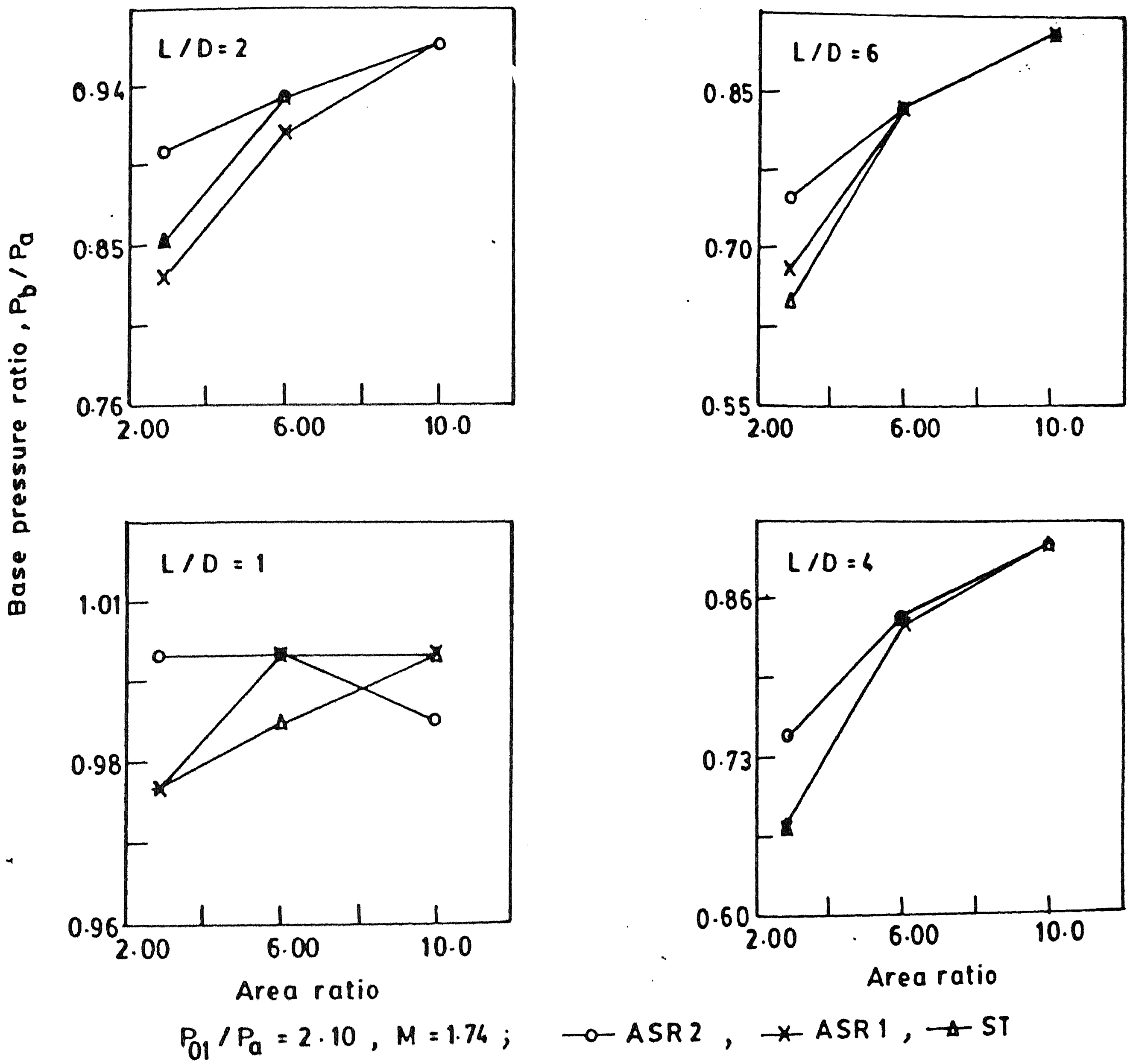


Figure 29: Base pressure variation with area ratio

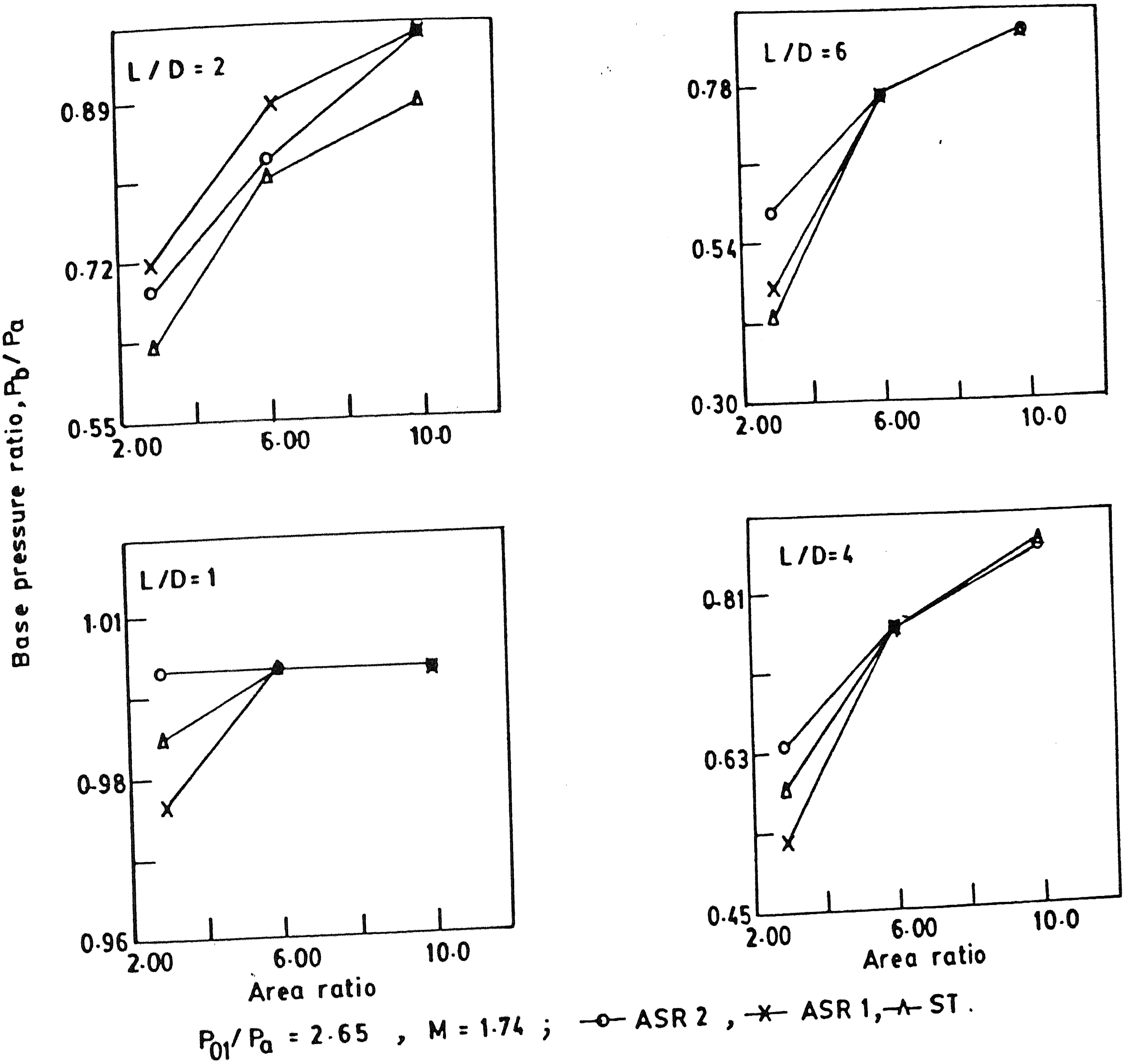


Figure 30: Base pressure variation with area ratio

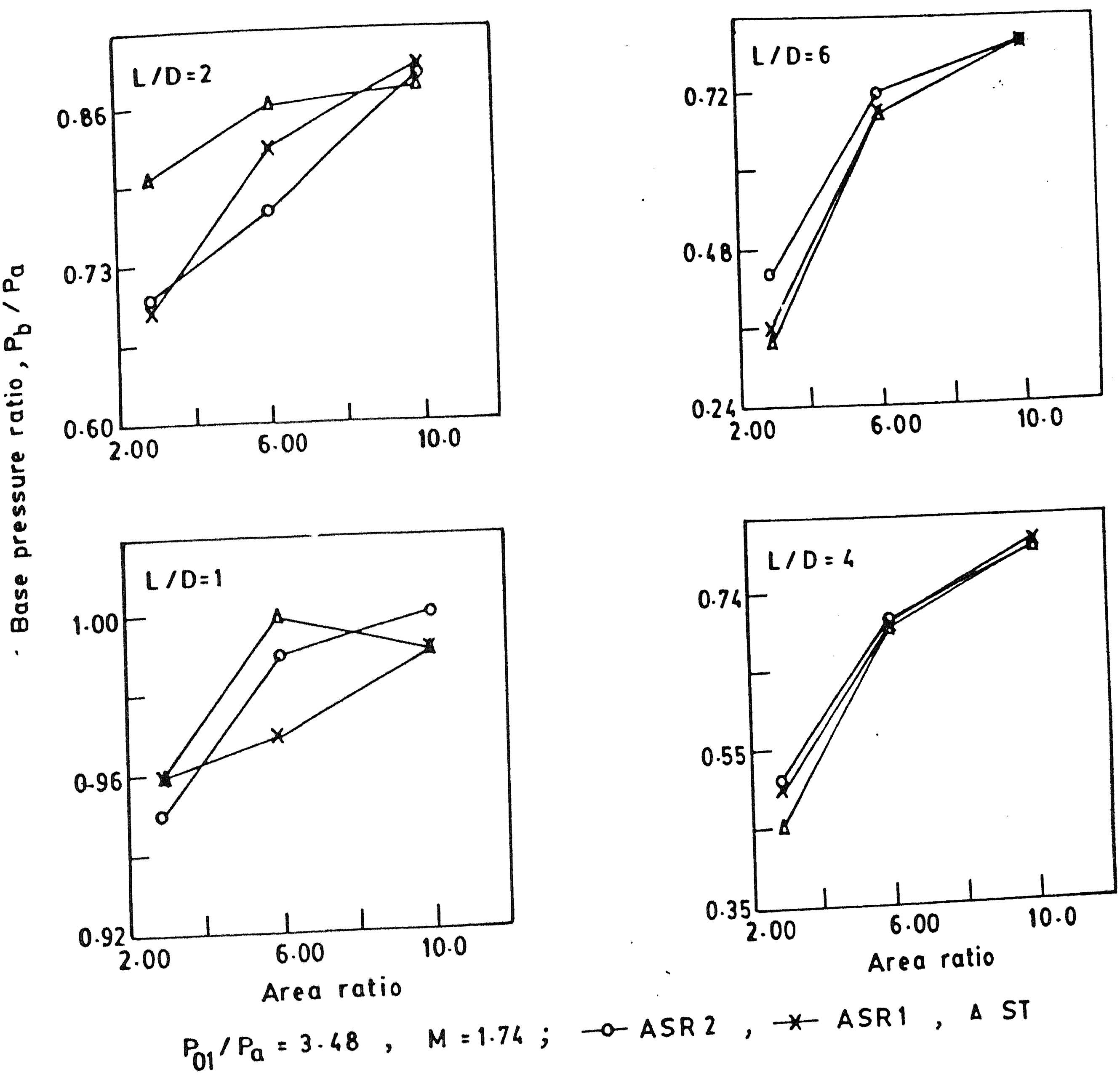


Figure 31: Base pressure variation with area ratio

different pressure ratio. As this was discussed earlier, this is due to the inability of the flow to attach with the enlarged duct on its expansion from the nozzle.

4.1.5 Oscillations of Base Pressure

The base pressure was found to show mild oscillations above and below its mean value, recorded as the base pressure, for subsonic value of nozzle exit Mach number. However, for supersonic values of nozzle exit Mach number the base flow showed significant oscillations. Further these oscillations were found to be violent for convergent divergent nozzles and was almost negligible for parallel nozzles designed with method of characteristics. The aspect ratio of the cavity is also of considerable influence on all Mach numbers of the convergent divergent nozzles. It is interesting to note that even the secondary disturbances created by the cavities get suppressed when the suddenly expanded flow field is from parallel nozzles. The above mentioned oscillatory pattern of the base pressure is due to the wave structure of the supersonic flow which is generated when the supersonic flow is experiencing a sudden relief combined to the divergence of the stream lines which are exiting from the convergent–divergent nozzles. In the parallel nozzles even though the flow from the nozzle is experiencing sudden relief, the expansion fan formed outwardly from the nozzle exit takes the flow isentropically to the base region, thereby ensuring establishment of base pressures without oscillations.

The oscillations of base pressure seems to be independent of the L/D of the enlargement. The base pressure oscillations for different combinations of parameters of the present experimental study is given in table 2 . The present study indicates severe oscillations of base pressure for area ratio 2.89, at all the primary pressure ratios of the study. In fact, as predicted by Rathakrishnan et al [60], the present

parametric combinations as given in Table 2 seem to be those resulting in enhancement of oscillations instead of suppression. Oscillations observed were more violent for the models with cavity aspect ratio 2 for area ratio 2.89.

4.1.6 Variation of Wall Pressure Along the Enlarged Duct

The pressures at the inner surface of the enlarged duct along its length were measured by wall pressure tappings provided as shown in Fig. 3. Care was taken to ensure that the tappings were in perfect line with the duct inner surface. In all cavities one pressure tap was provided at the middle of the cavity. Measurements of wall pressures were made for all the combinations of the parameters of the present experimental study. Few representative results showing typical development of flow along the length of the enlarged duct are presented here.

For supersonic Mach numbers, Mach 1.74 at the nozzle exit has been chosen for the presentation of results. Results of pressure variation along the enlarged duct for the three area ratios of 10,6 and 2.89 are shown in figures 32, 33 and 34 respectively, with cavity aspect ratio and L/D as the parameters. The wall pressure has been non-dimensionalized with the ambient atmospheric pressure to which the flow from the enlarged duct was discharged. The axial distance along the enlarged duct has been non-dimensionalized with its length. From these results it is seen that the flow requires the length of the duct to be between 4 to 6 times the diameter for proper flow development taking the pressure which is low at the level of base pressure at the beginning of the enlarged duct to that of ambient atmosphere at the duct exit. When the length is less than 4,the flow does not find enough contact area available for its development taking its pressure from base pressure to atmospheric pressure at the exit, as it is clearly seen for L/D equal to 2 and area ratios 2.89 and 6. For area ratio 10, since the establishment of base flow itself is not possible, the flow just

Table 2: Parametric Combinations for observed oscillations

Nozzle designation	Area ratio	Primary pressure ratio	L/D ratio	Cavity aspect ratio
N_2	6.00	3.48	5	2
N_2	6.00	3.48	6	2
N_2	6.00	3.21 & 3.48	8	2
N_2	6.00	3.21 & 3.48	10	2
N_2	2.89	3.48	6	1
N_2	2.89	2.65	2 & 3	2
N_2	2.89	2.10 & 2.38	4	2
N_2	2.89	2.10 & 2.38	5	2
N_2	2.89	3.21	5	2
N_2	2.89	2.10 & 2.38	6	2
N_2	2.89	2.38 & 3.21	8	2
N_2	2.89	2.38	10	2
N_{2I}	6.00	3.21 & 3.48	8	2
N_{2I}	6.00	2.93 & 3.21	10	2
N_{2I}	6.00	3.48	10	2
N_{2I}	2.89	2.65	2	1
N_{2I}	2.89	2.10	10	2
N_3	6.00	3.48	4	1
N_3	6.00	2.65 & 2.93	2	2
N_3	6.00	3.48	3	2
N_3	2.89	2.65	2	2
N_3	2.89	2.38	3	2
N_3	2.89	2.10 & 2.38	4	2
N_3	2.89	2.93	4	2
N_3	2.89	2.10 & 2.38	5	2
N_3	2.89	2.93	5	2
N_3	2.89	2.10 & 2.38	6	2
N_3	2.89	2.93	6	2
N_3	2.89	2.10 & 2.38	8	2
N_3	2.89	2.93	8	2
N_3	2.89	2.10 & 2.38	10	2
N_3	2.89	2.93 & 3.21	10	2
N_{3I}	2.89	2.65	8	1
N_{3I}	2.89	2.38	2	2
N_{3I}	2.89	2.93	5	2
N_4	6.00	2.65	3	2
N_4	2.89	3.48	4	1
N_4	2.89	2.93	8	1
N_4	2.89	3.21	10	1
N_4	2.89	2.38	4	2
N_4	2.89	2.38	6	2
N_4	2.89	2.38 & 2.65	8	2
N_4	2.89	2.38 & 3.48	10	2

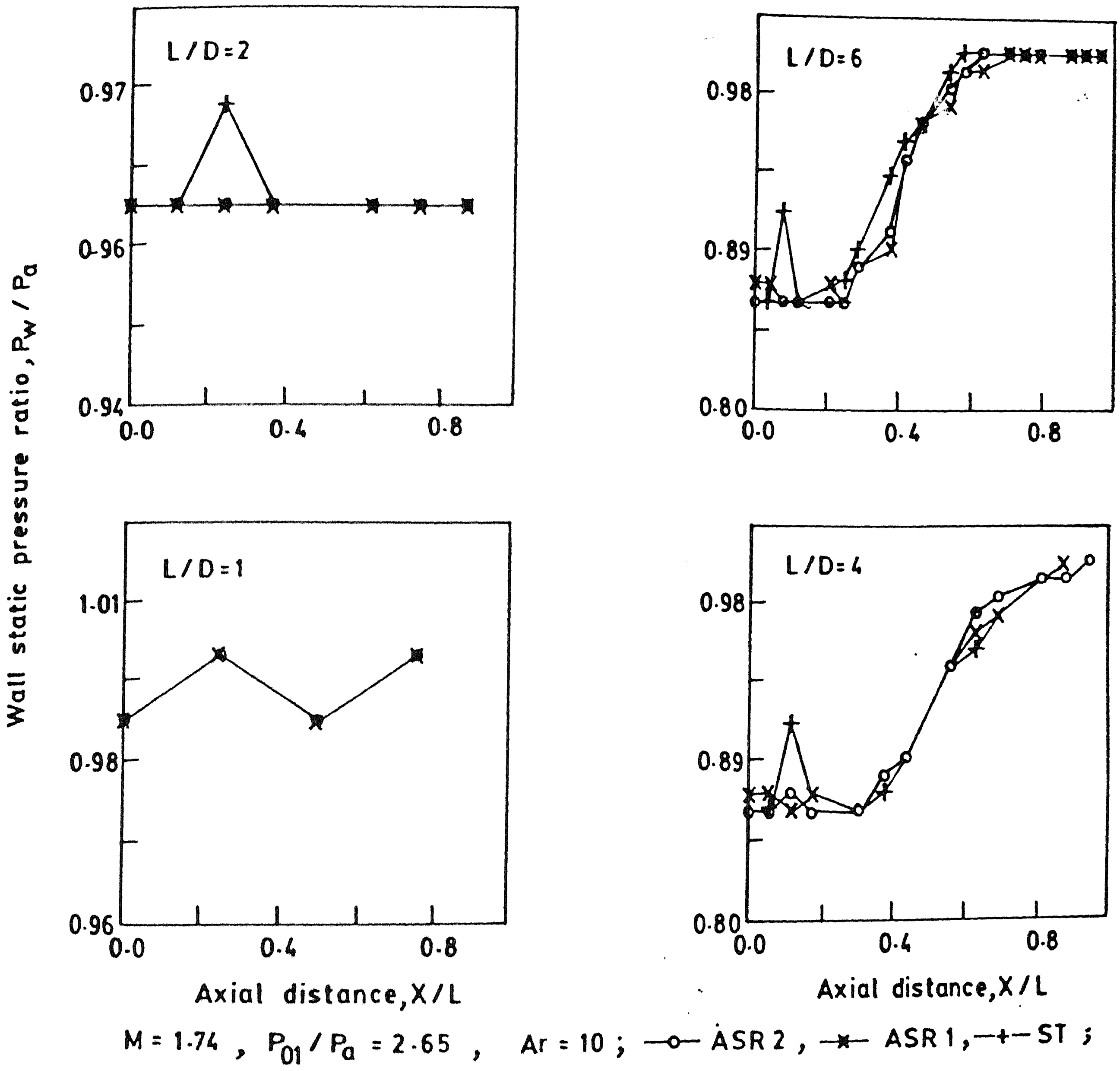


Figure 32: Wall pressure variation with X/L

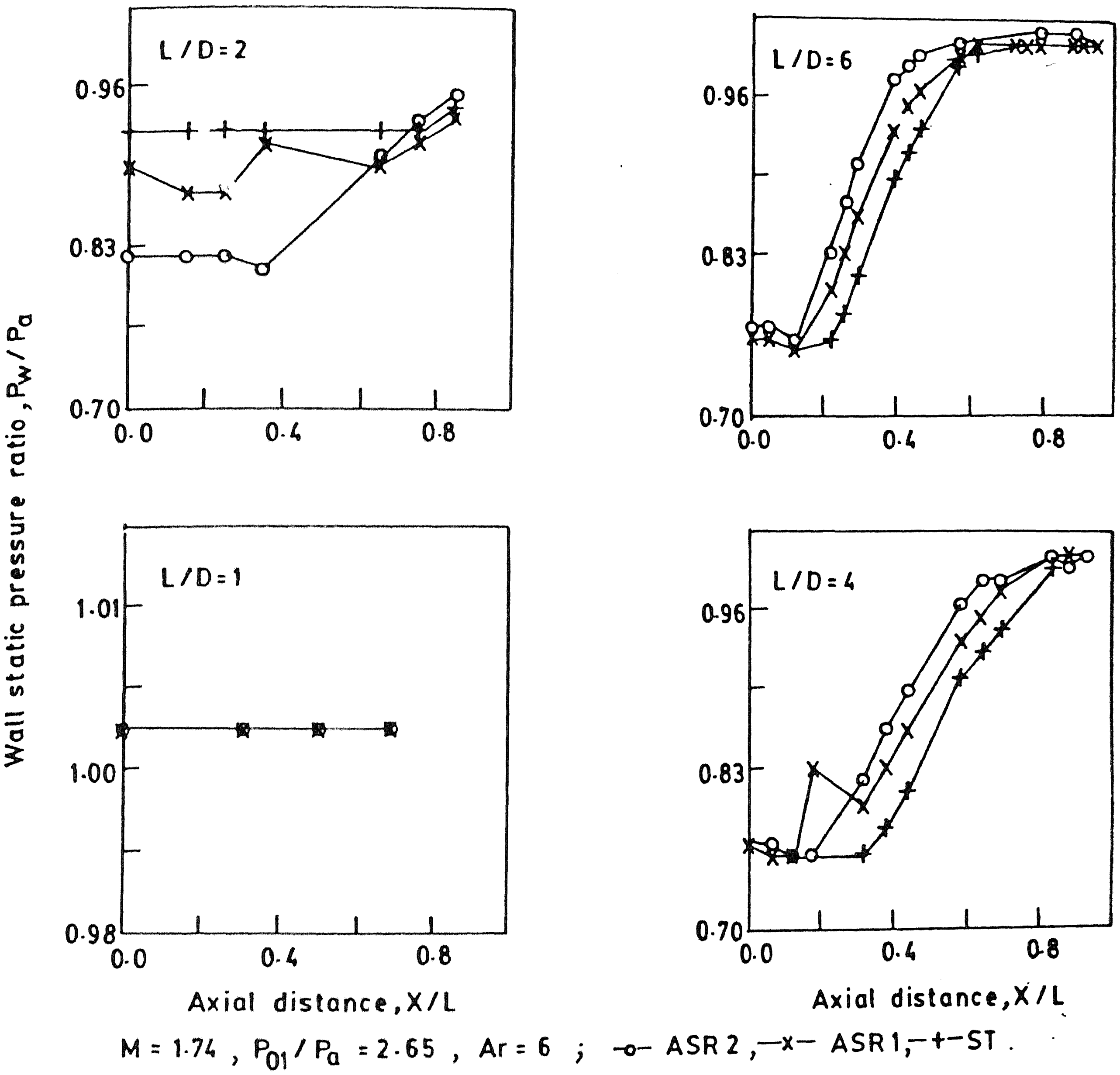


Figure 33: Wall pressure variation with X/L

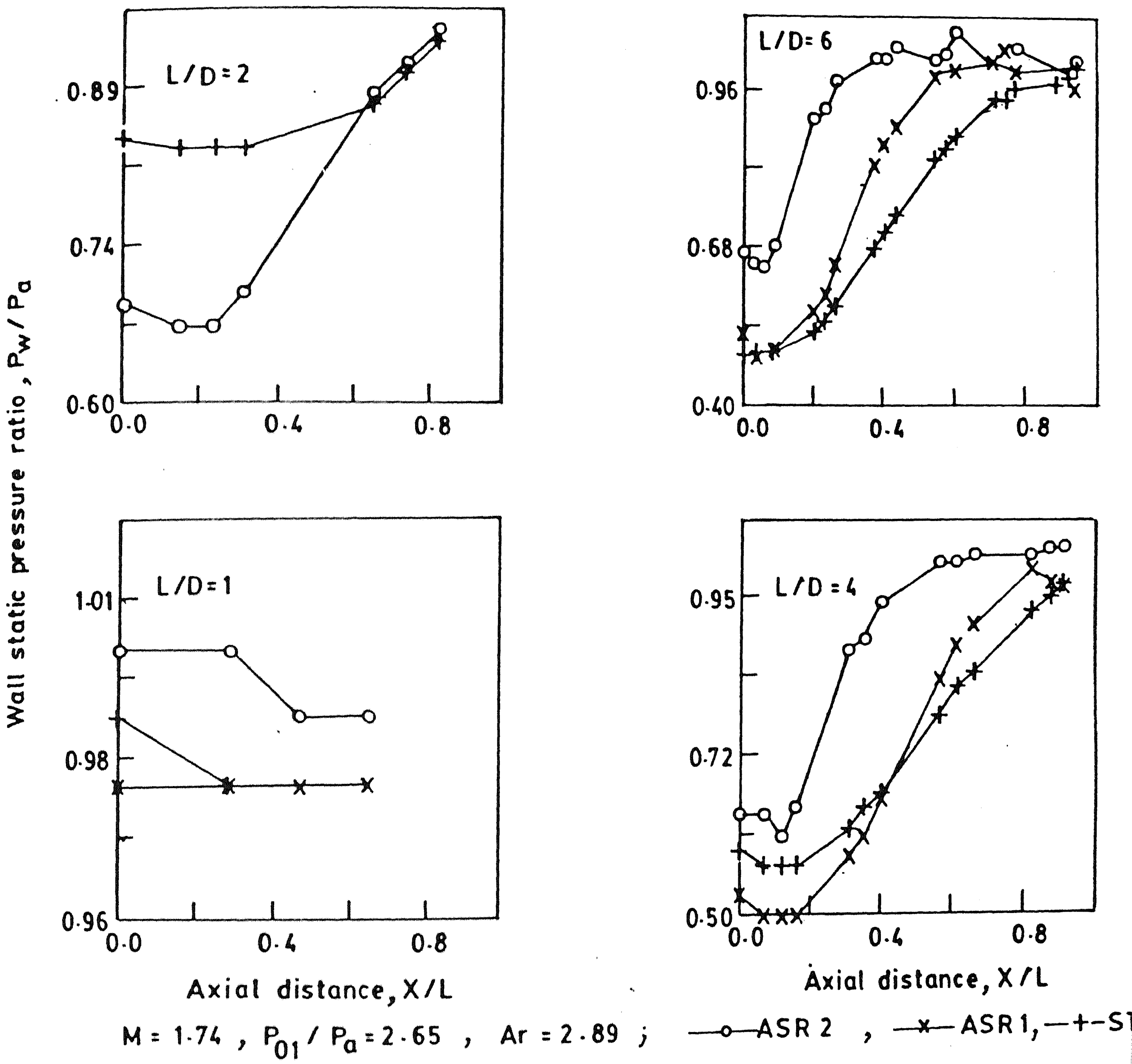
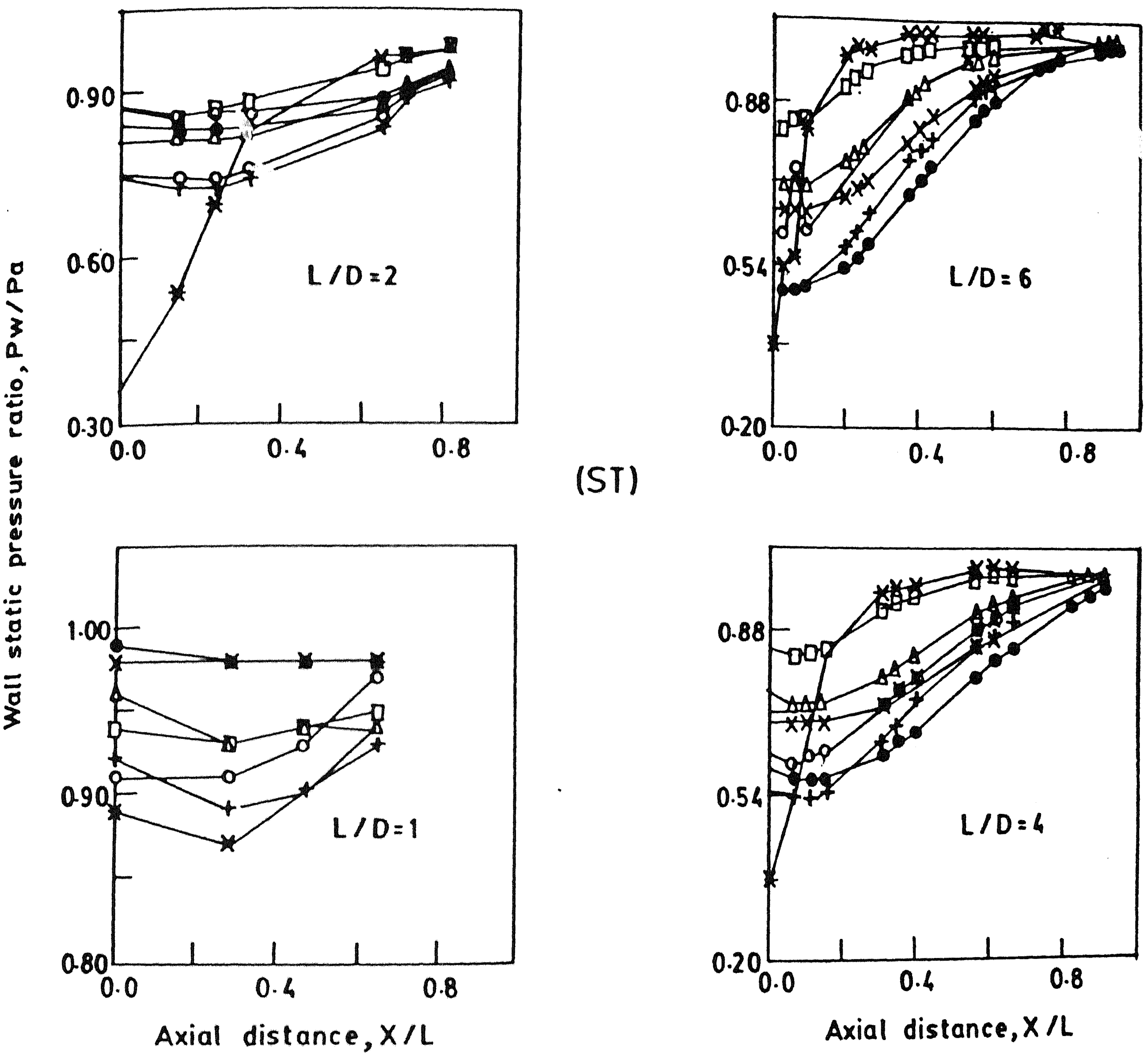


Figure 34: Wall pressure variation with X/L

gets discharged to ambient atmosphere almost right from the beginning of the duct. For L/D more than four, the flow exhibits almost uniform pressure upto 20% of the duct length, and then steeply rises to the level of the ambient atmosphere. This rise becomes steeper with increase in L/D for area ratio 6 and 10. However, for area ratio 2.89, the pressure decreases below the base pressure in the vicinity of the base region and then starts increasing steeply attaining the ambient pressure at about 90% of the length from cavity aspect ratio 1 and the plane duct. But for the cavity aspect ratio 2, it attains atmospheric pressure within 60% of length for L/D=4,and within 40% of length for L/D=6, implying that only for area ratio 2.89, the effect of aspect ratio is strong on the flow development in the enlarged duct whereas for area ratio 6, the effect of aspect ratio on flow development is less significant, and for area ratio 10, it is almost insignificant. However, for area ratio 6, the region of steep pressure rise,the effect of aspect ratio is to augment the pressure rise even though near the base and towards the duct exit its influence is almost nil.

4.1.7 Wall Pressure Variations for Supersonic Mach Numbers (1-2.75)

The results of wall static pressure variation along the enlarged duct length for the supersonic Mach numbers of the present experimental study, from Mach 1 to Mach 2.75 for area ratio 2.89 are presented in figures 35,36 and 37. Although six primary pressures 2.10,2.38,2.65, 2.93,3.21 and 3.48 have been used for experimentations, but primary pressure 2.65 has been taken as representative. The effect of change of model area ratio on flow development is already discussed earlier. From these results it is seen that as one could expect, the enlarged duct should have a definite minimum length for the supersonic flow from the nozzle exit to decelerate by increasing its static pressure from the base pressure value to atmospheric pressure level at the exit



P_{01}/P_a = 2.65 ; Ar = 2.89 ; □ M = 2.75 , ▲ 2.40 , × 2.23 , ○ 2.06 , ● 1.74 , + 1.58 , ✱ 1.00

Figure 35: Wall pressure variation with X/L

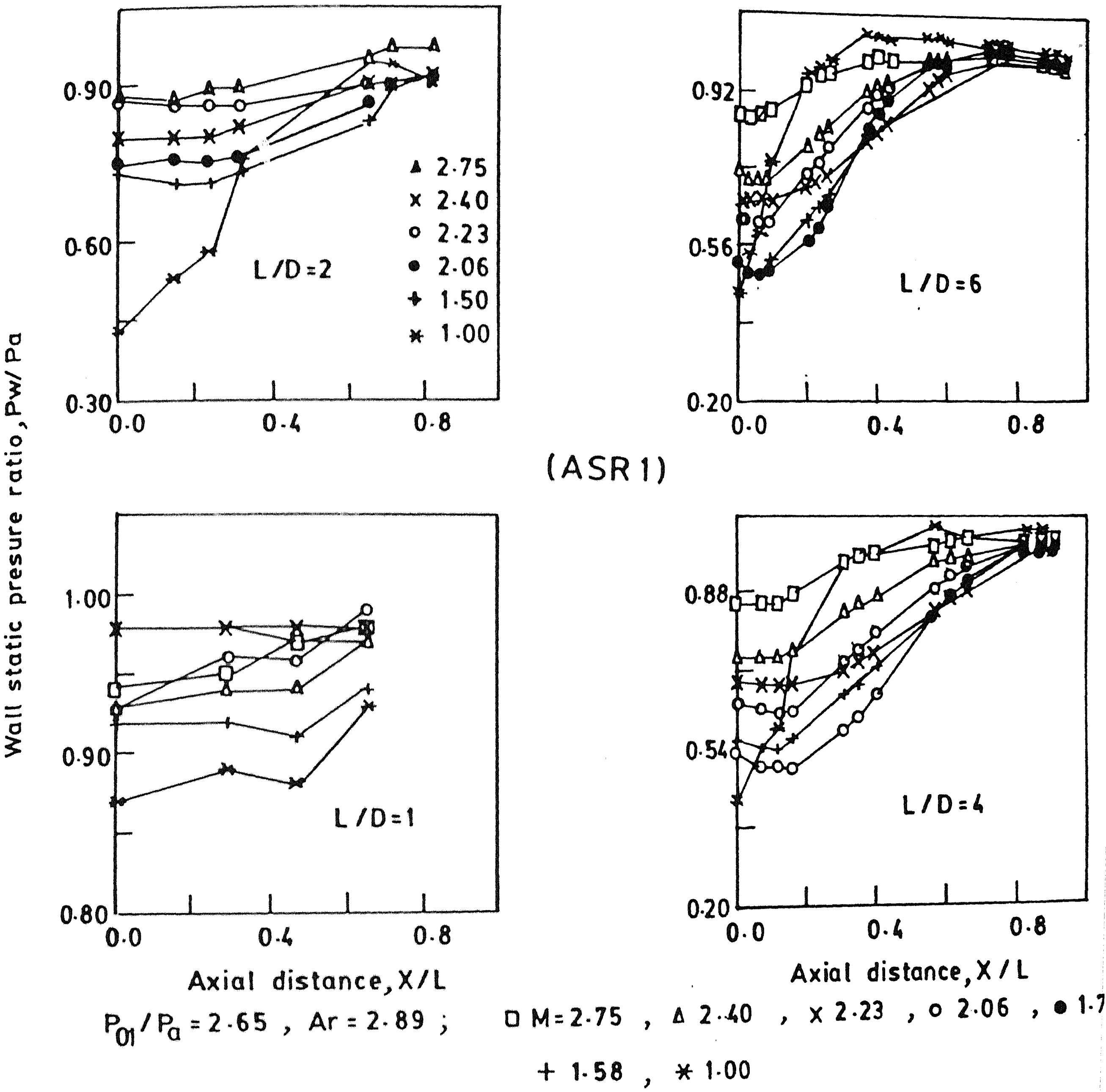


Figure 36: Wall pressure variation with X/L

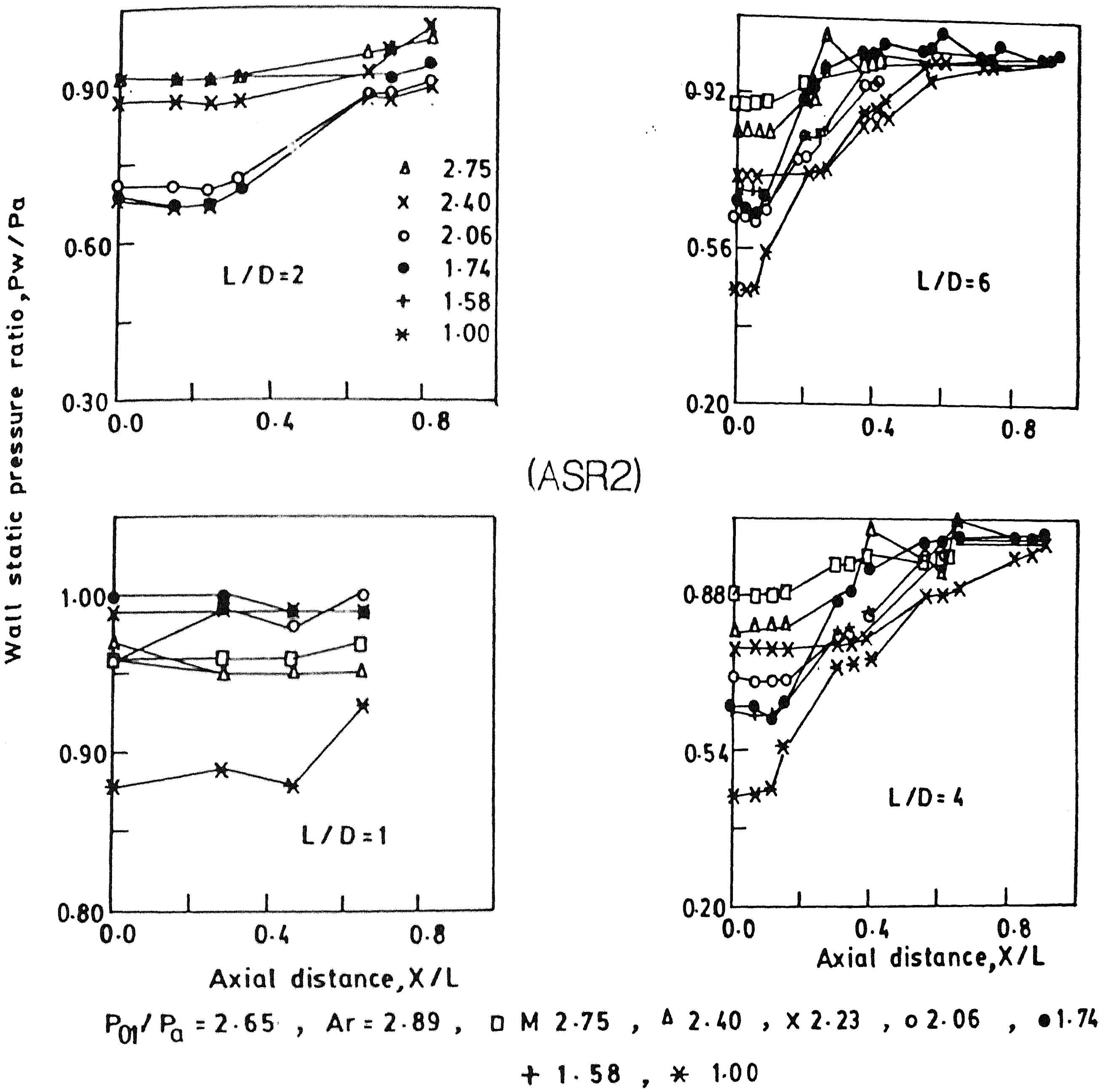


Figure 37: Wall pressure variation with X/L

of the duct. For the plane duct, this minimum is around six time the diameter. For enlarged duct with cavity this length is marginally less than that for the plane duct as seen from the plots as in the case of subsonic flows. When the length of the duct is very small, the flow does not seem to attach with the wall and develop further as it is seen from the results. The cavity with aspect ratio 2 is found to introduce disturbances which make the wall pressure development from base pressure level at the entry to enlarged duct to ambient pressure at its exit to take an oscillatory pattern, as seen from Fig.35. For cavity aspect ratio 1, there is no such noticeable oscillation of the wall static pressure variation. From these results it is obvious that once the flow negotiates the wave dominated base zone, its behavior is almost same as that of subsonic flow from the nozzle.

The results of wall static pressure variation along the enlarged duct for area ratio 6 are presented in figures 38, 39 and 40 for the plane surface and duct with annular cavities. These results once again reiterate that the duct should have a definite minimum length for the flow to expand to the level of ambient atmosphere for all Mach numbers. For this area ratio again, the minimum length is four times the diameter. When the length is increased beyond 4, the pressure plots show a tendency to combine into a single curve, levelling off at $P_w/P_a = 1$ for all Mach numbers from 1 to 2.75 of the present study. This merging phenomenon seems to improve with increase in annular cavity aspect ratio . This may be due to the fact that the secondary disturbance created by the cavities compel the main stream to attain uniformity of the pressure field at all Mach numbers, once the flow comes out of the base region.

The pressure fields of the enlarged duct with area ratio 10 are presented in figures 41, 42 and 43. The wall static pressure distribution for the straight walled duct shows considerable oscillation at Mach 1 whereas the oscillation is suppressed

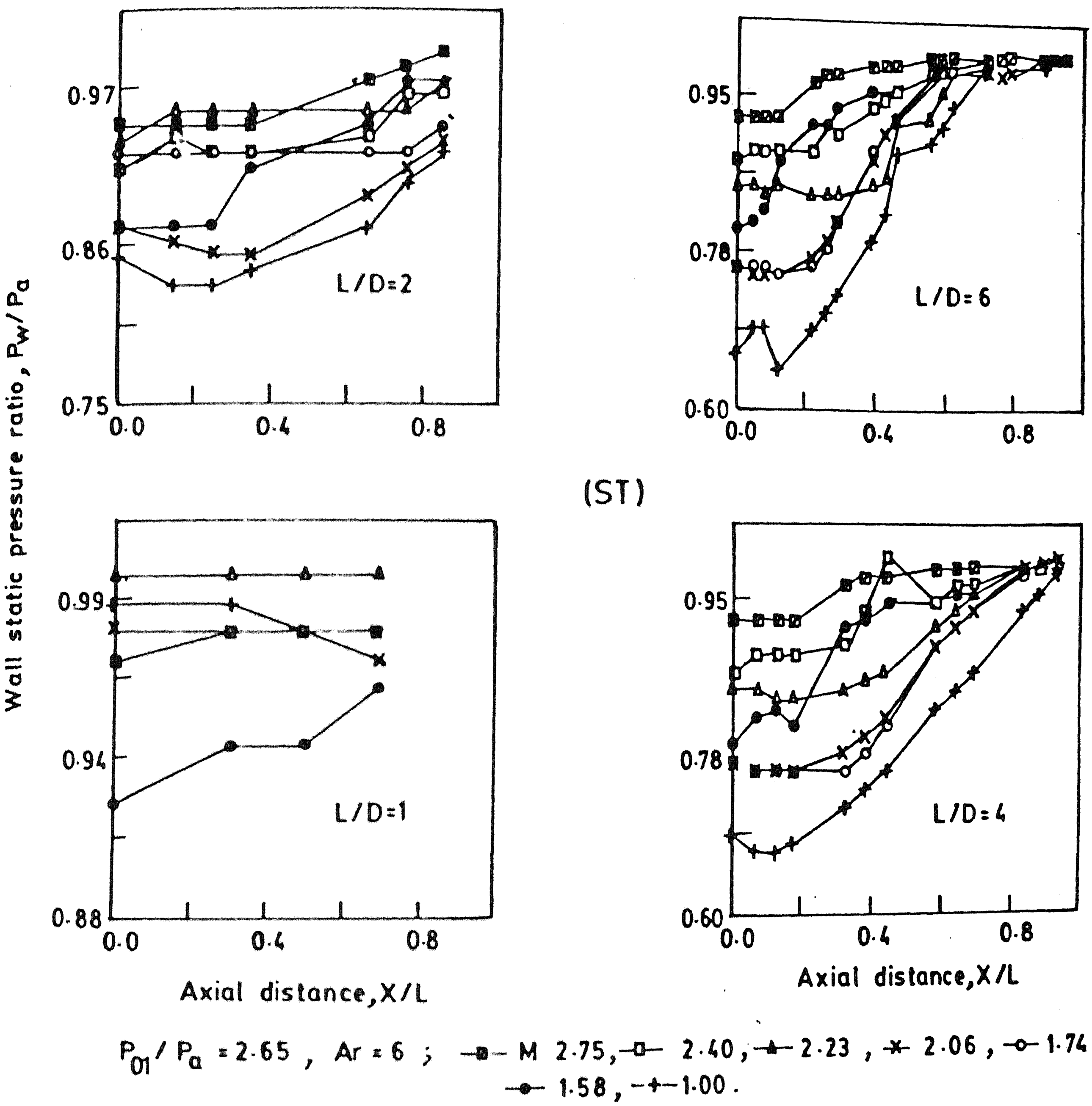
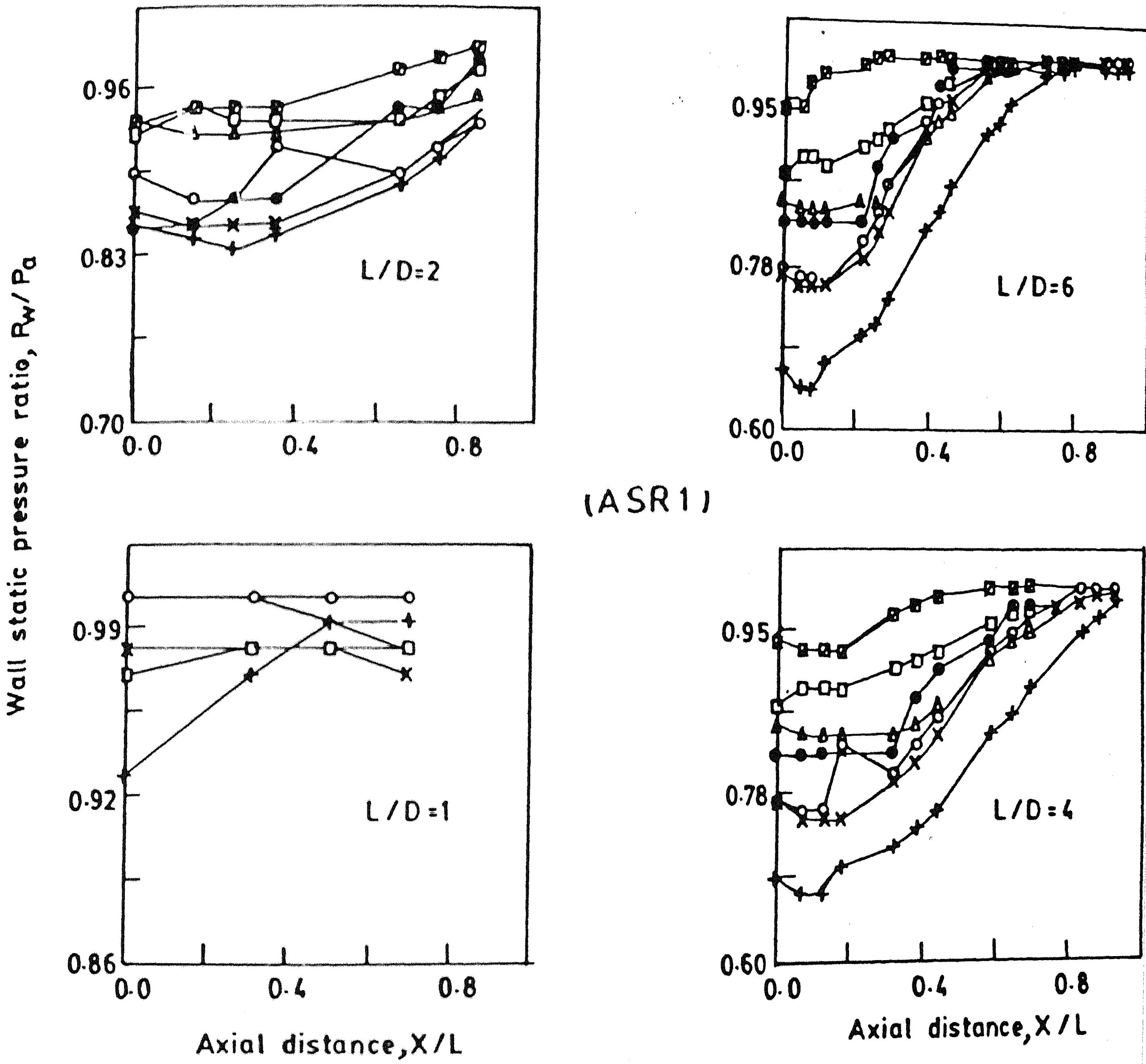


Figure 38: Wall pressure variation with X/L



P_{01}/P_a = 2.65 , Ar = 6 ; M = 2.75, 2.40, 2.23, 2.06, 1.74, 1.58, 1.00;

Figure 39: Wall pressure variation with X/L

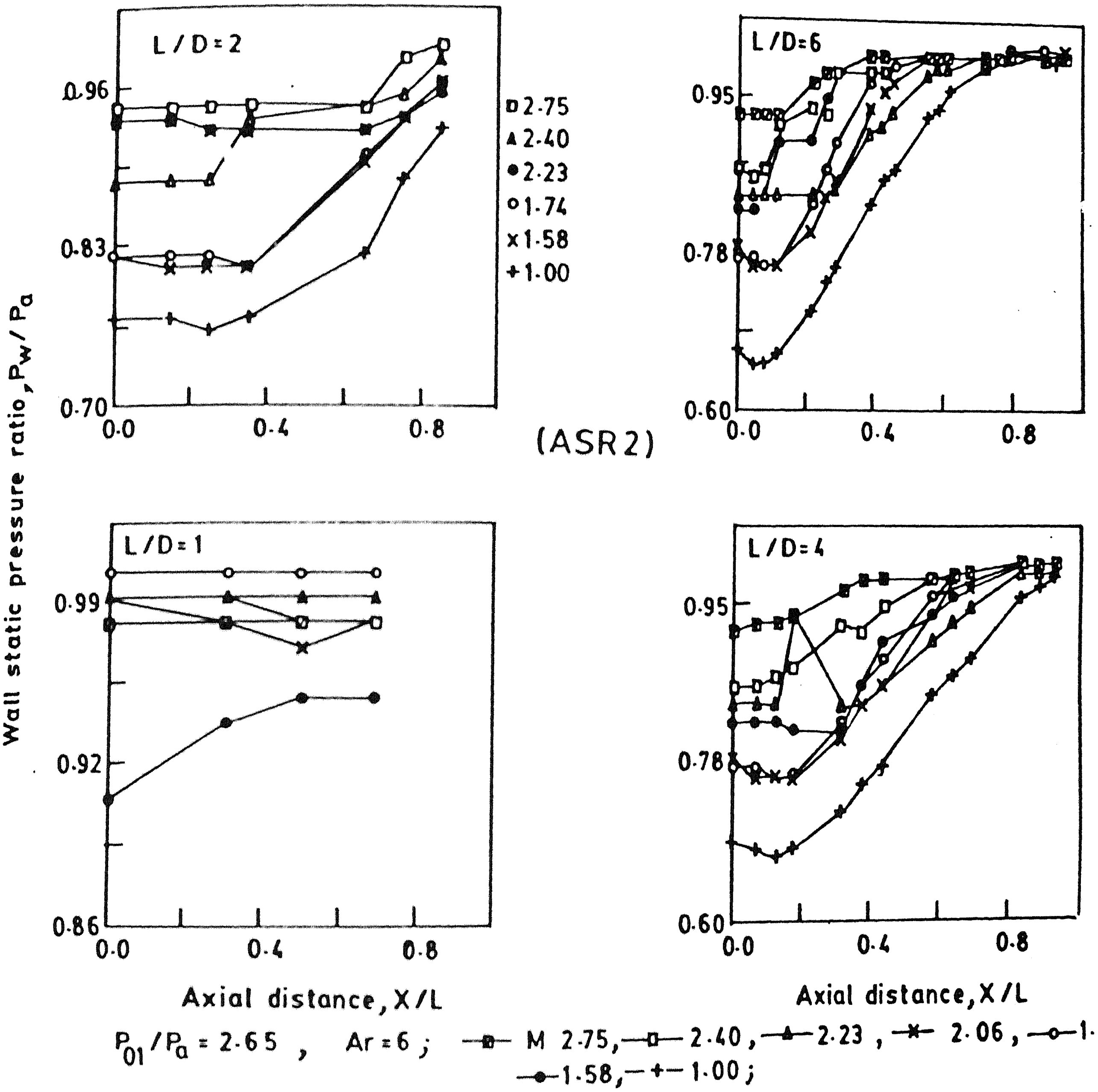


Figure 40: Wall pressure variation with X/L

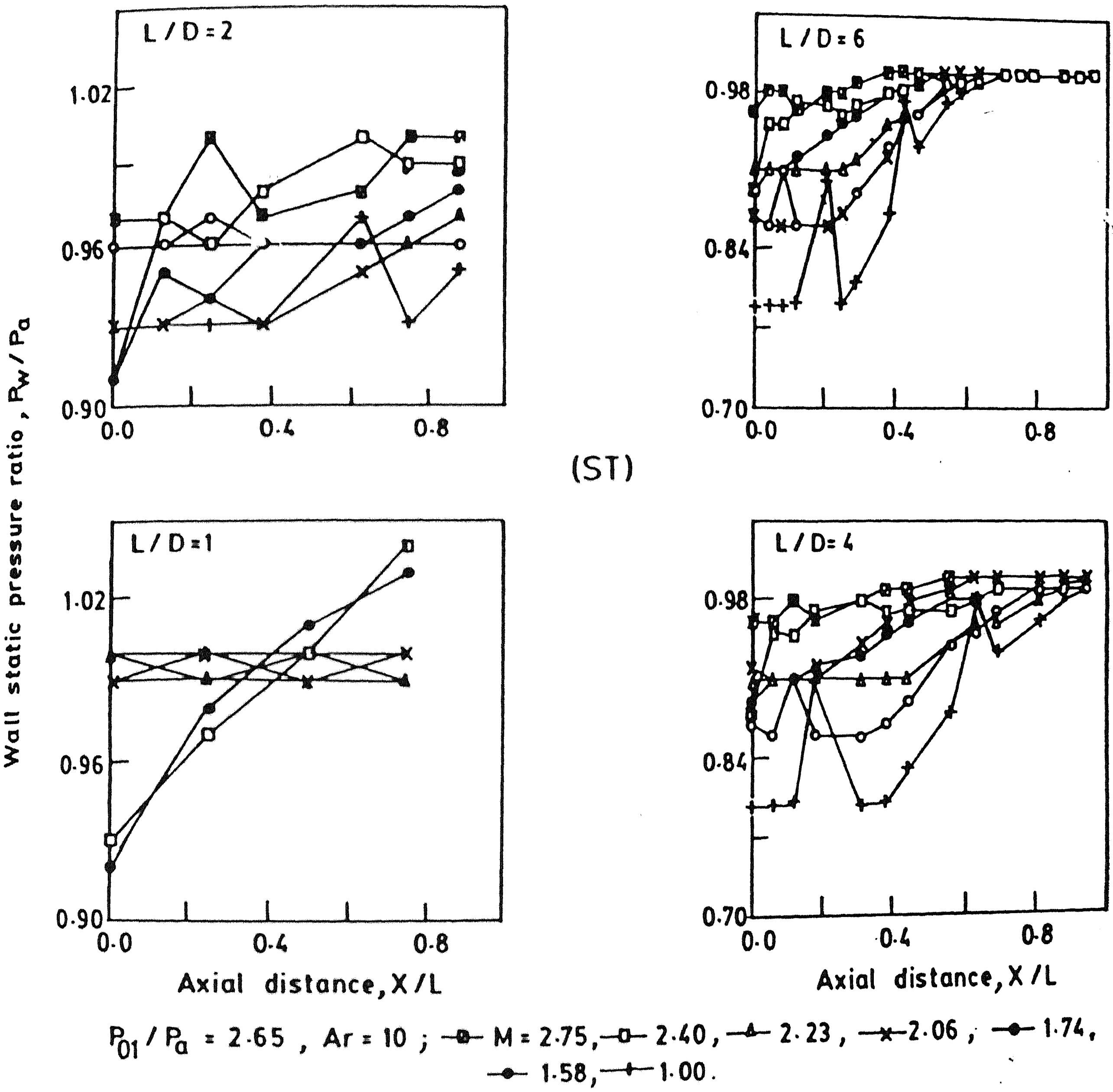


Figure 41: Wall pressure variation with X/L

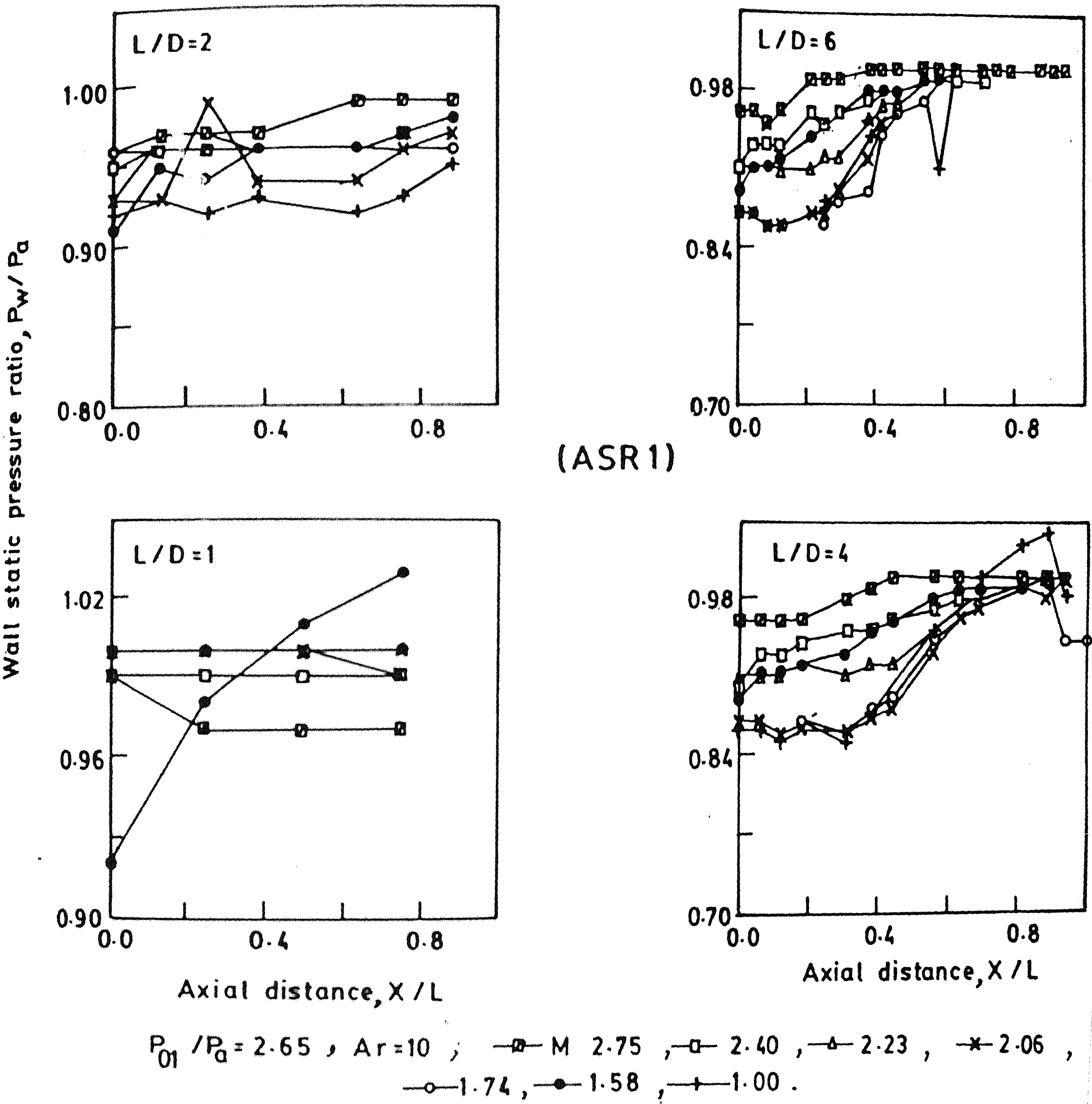


Figure 42: Wall pressure variation with X/L

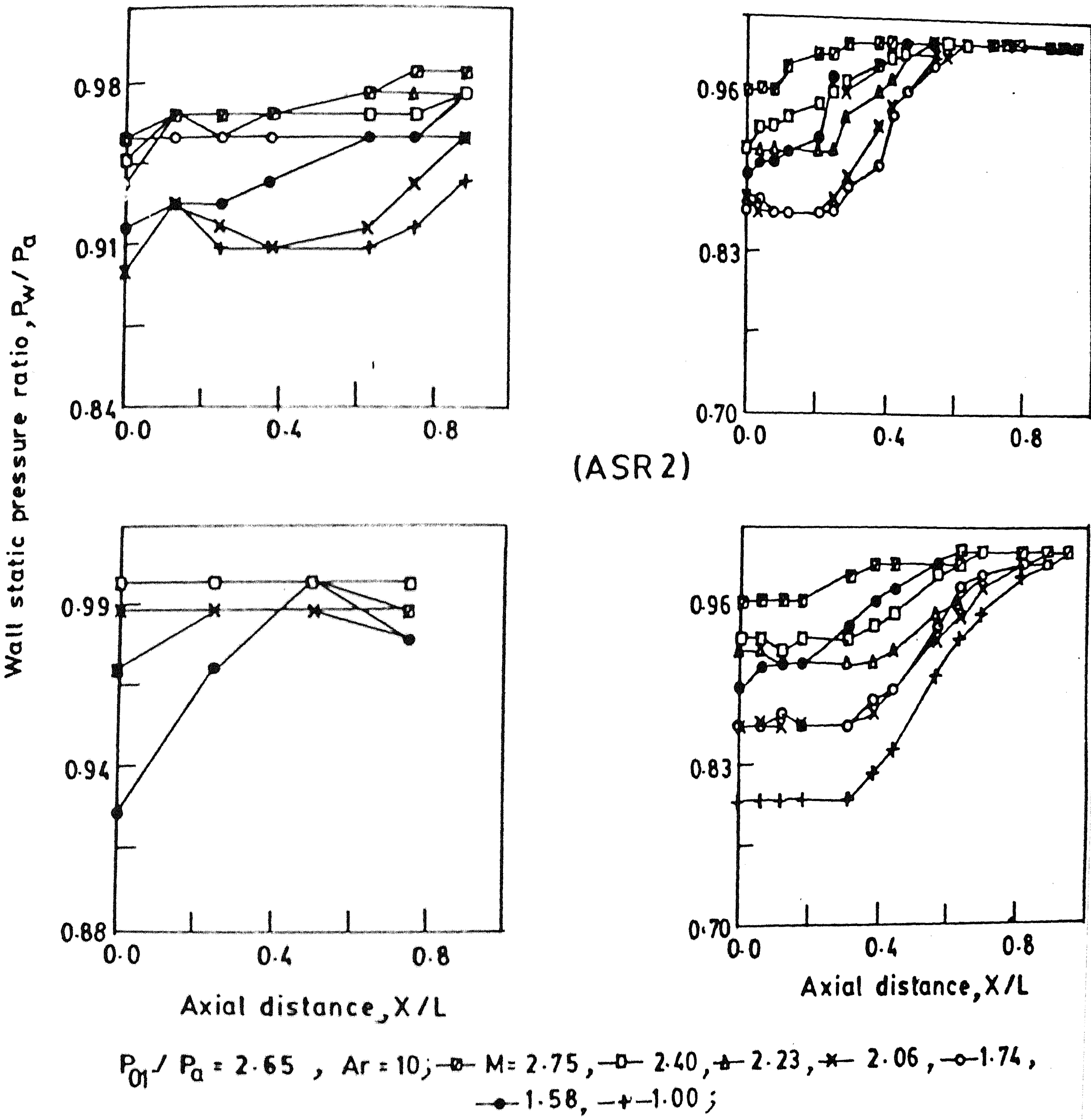


Figure 43: Wall pressure variation with X/L

considerably by the annular cavity with aspect ratio 1. Whereas for aspect ratio 2 these oscillations are almost completely suppressed. Further, when the L/D is more than 4, the pressure plots actually merge into a single curve at $P_w/P_a = 1$ beyond 60% of the duct length. This tendency of the pressure field attaining complete adaption is due to the significant relief effect experienced by the flow for this area ratio. Here again the duct must have a definite minimum length for proper developement of the flow.

From the above results of wall pressure variation along the length of the enlarged duct with and without cavities, it is evident that at supersonic nozzle exit Mach numbers, the duct L/D should be more than 4 for proper developement of the flow. This L/D requirement of flow development is independent of the area ratio of model. Further the cavity seems to be effective in suppressing the oscillation when its effect is combined with considerable relief effect provided by large area ratio. The oscillation suppression seems to improve with increase in annular cavity aspect ratio from 1 to 2.

4.1.8 Variation of Pressure Loss with Nozzle Exit Mach Number

The total pressure loss at all flow conditions of the present study was estimated as percentage pressure loss,from the measurements of the total pressure at the exit plane of the enlarged duct and the settling chamber pressure. The total pressure at the exit of the enlarged duct was measured using a Pitot probe located at the center of the exit plane in conjunction with a U tube mercury manometer.

The measured total pressure loss as a function of nozzle exit Mach number is presented in figures 44, 45 and 46 for the three primary pressure ratios of 2.10,2.65 and 3.48 for model area ratio 10. From these Figures it is seen that the pressure ratio

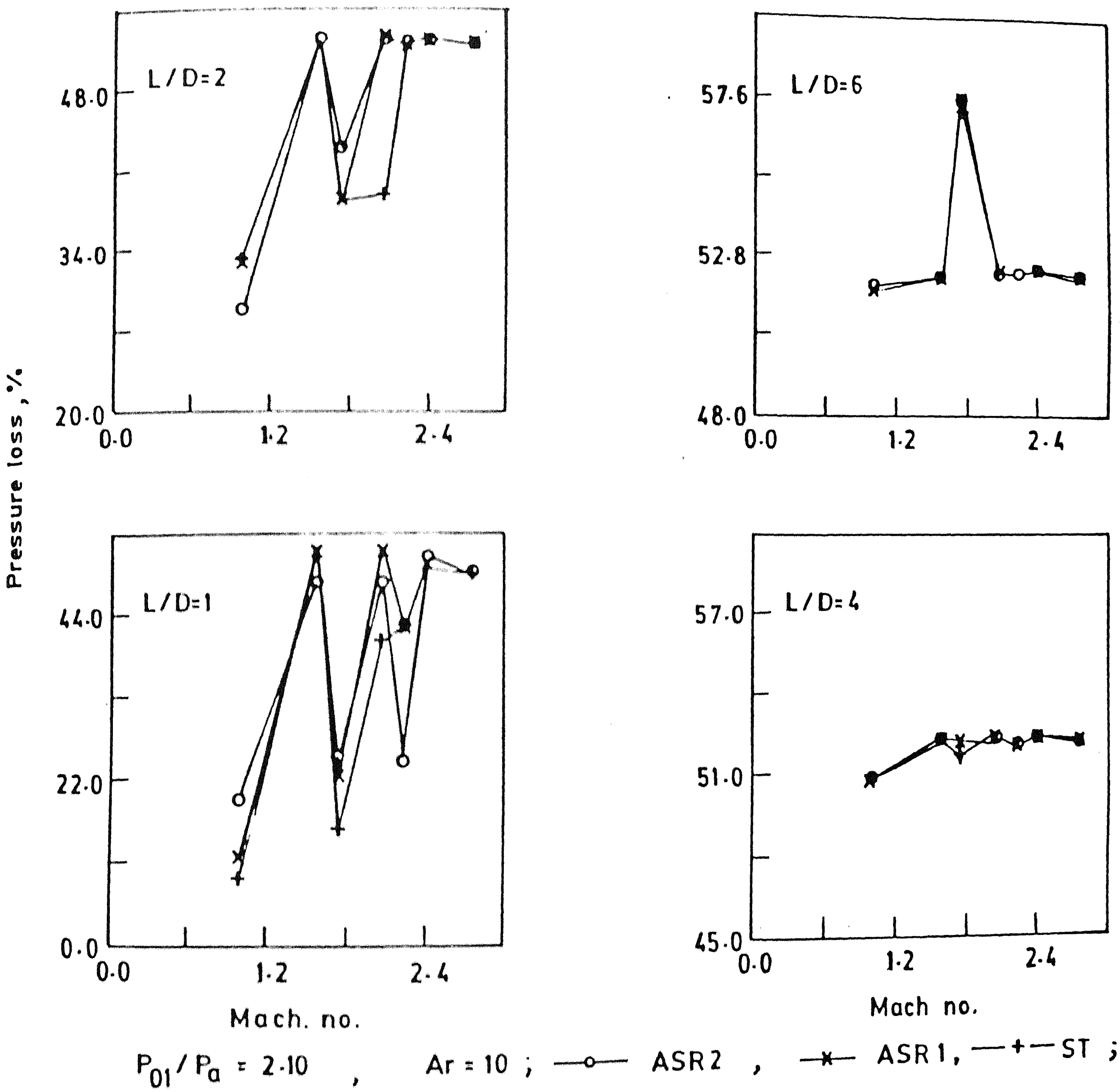


Figure 44: Pressure loss variation with Mach number

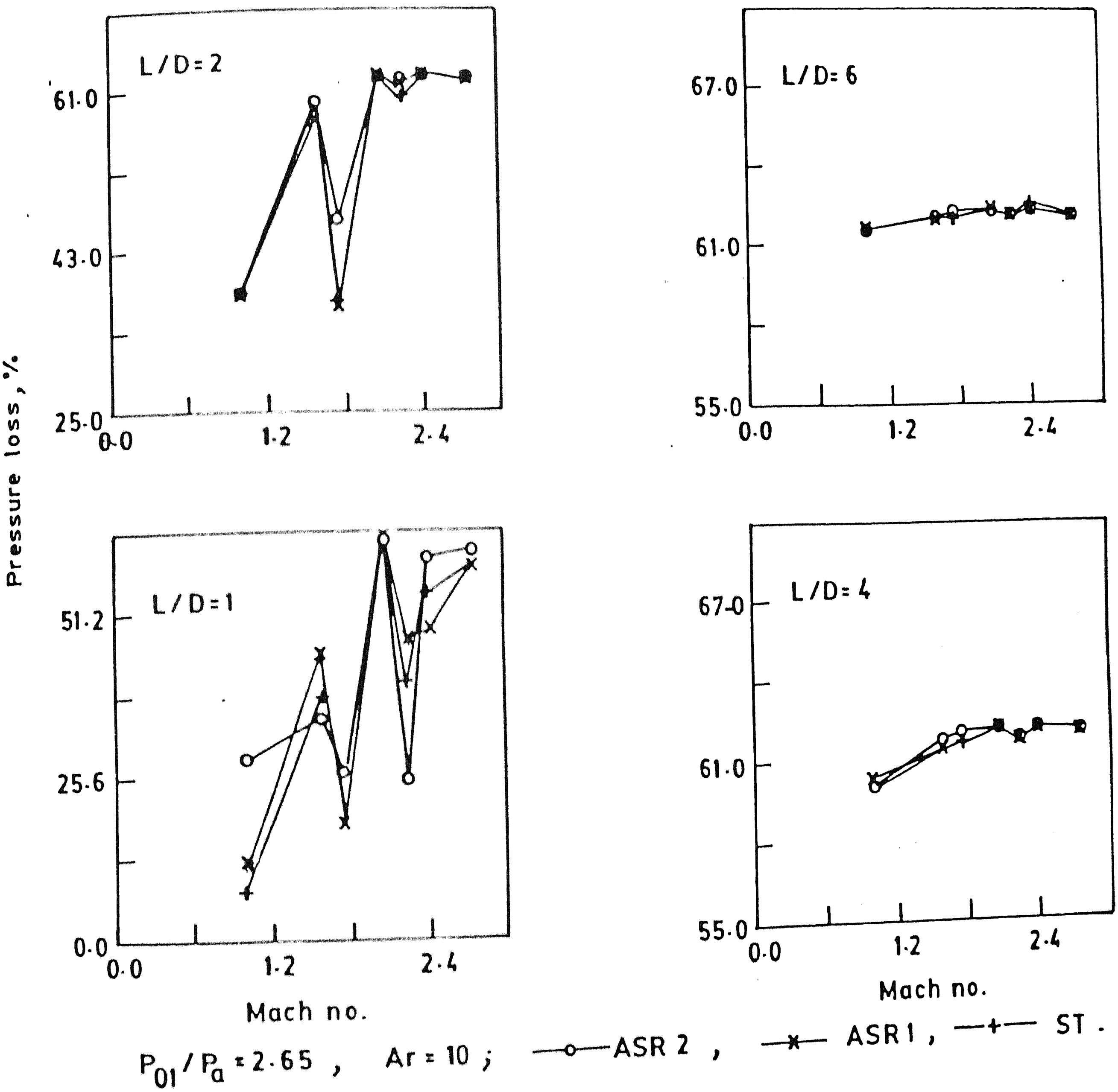


Figure 45: Pressure loss variation with Mach number

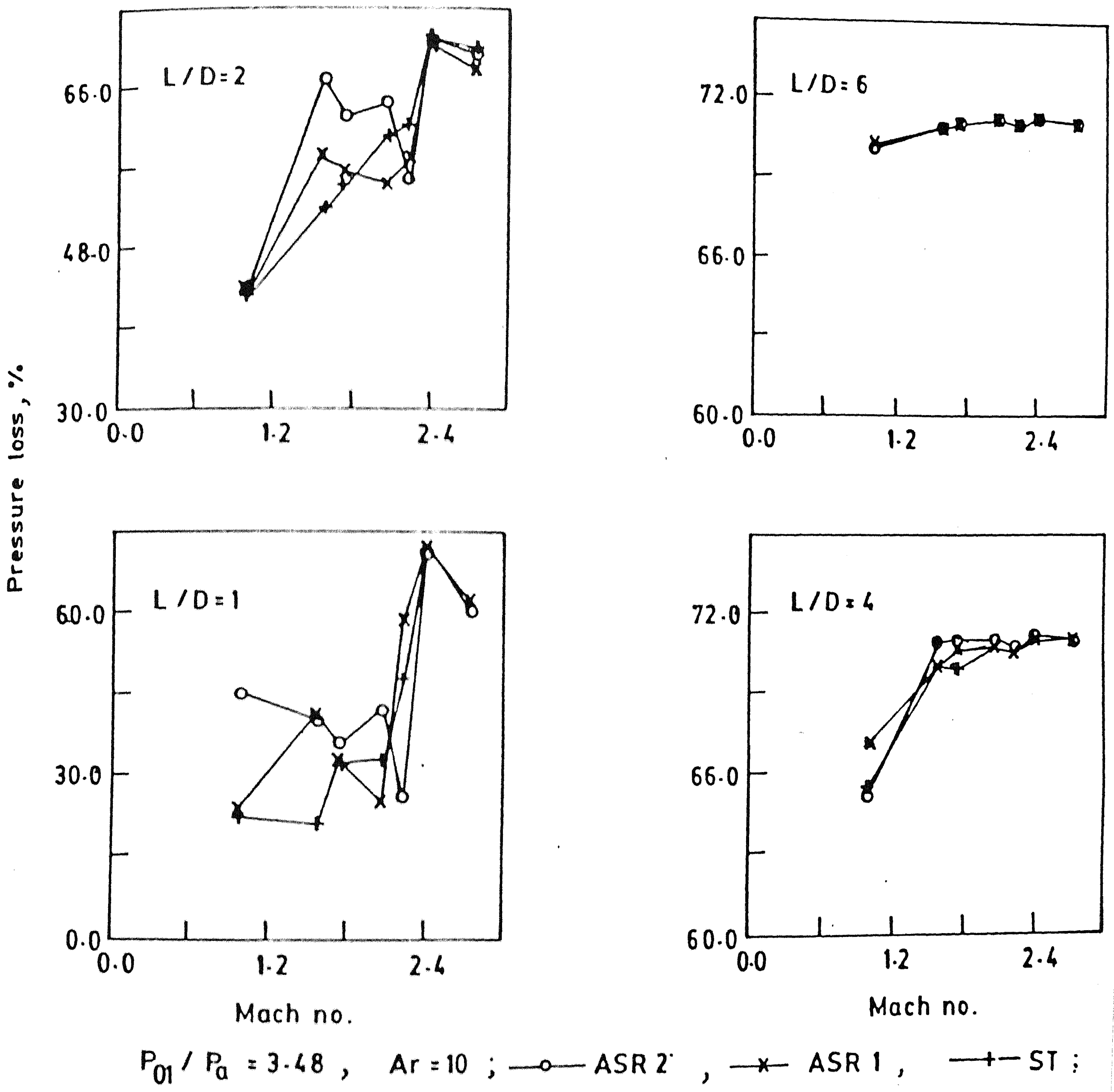


Figure 46: Pressure loss variation with Mach number

shows a random behavior with L/D upto 2 and for higher L/D from 4, there is a well defined variation of pressure loss with Mach number showing a marginal increase with Mach number in the range of 1 to 1.58 and then it remains almost constant with Mach number. This kind of trend of total pressure loss variation with Mach number showing a random variation with Mach number may be attributed to the wave structure of the supersonic field prevailing inside the enlarged duct in combination with the relief effect experienced by the flow when the length of the duct is short. When the duct length is considerably large for the waves from the nozzle exit to get reflected from the duct wall, the flow after passing through few such reflected waves experiences a smooth development leading to continuous deceleration and increases the pressure to atmospheric level as it reaches the duct exit. This phenomenon takes place with all Mach numbers when the length is sufficiently long and the loss experienced by the flow exhibits almost same level at all Mach numbers. Further, it is obvious from these results that the cavity aspect ratio effect on the pressure loss shows significant influence for model L/D ratio less than 3. For L/D more than 4 the effect of cavity on pressure loss is only marginal.

Pressure loss results for area ratio 6 are presented in figures 47 to 49, all other parameters remaining same as above. From these figures again it is observed that for model with L/D less than 2, the pressure loss variation with Mach number is random and for L/D 4 and above the pressure loss shows a steep increase with Mach number in the range of M from 1 to 1.58 and then shows only a marginal increase for Mach numbers more than 1.58. This trend is same for all the pressure ratios tested. The aspect ratio of the cavity influences the pressure loss significantly even for the ducts with L/D more than 4. This may be due to the fact that when the area ratio decreases from 10 to 6, the relief effect experienced by the flow gets reduced considerably and the secondary disturbance in the form of vortices introduced by

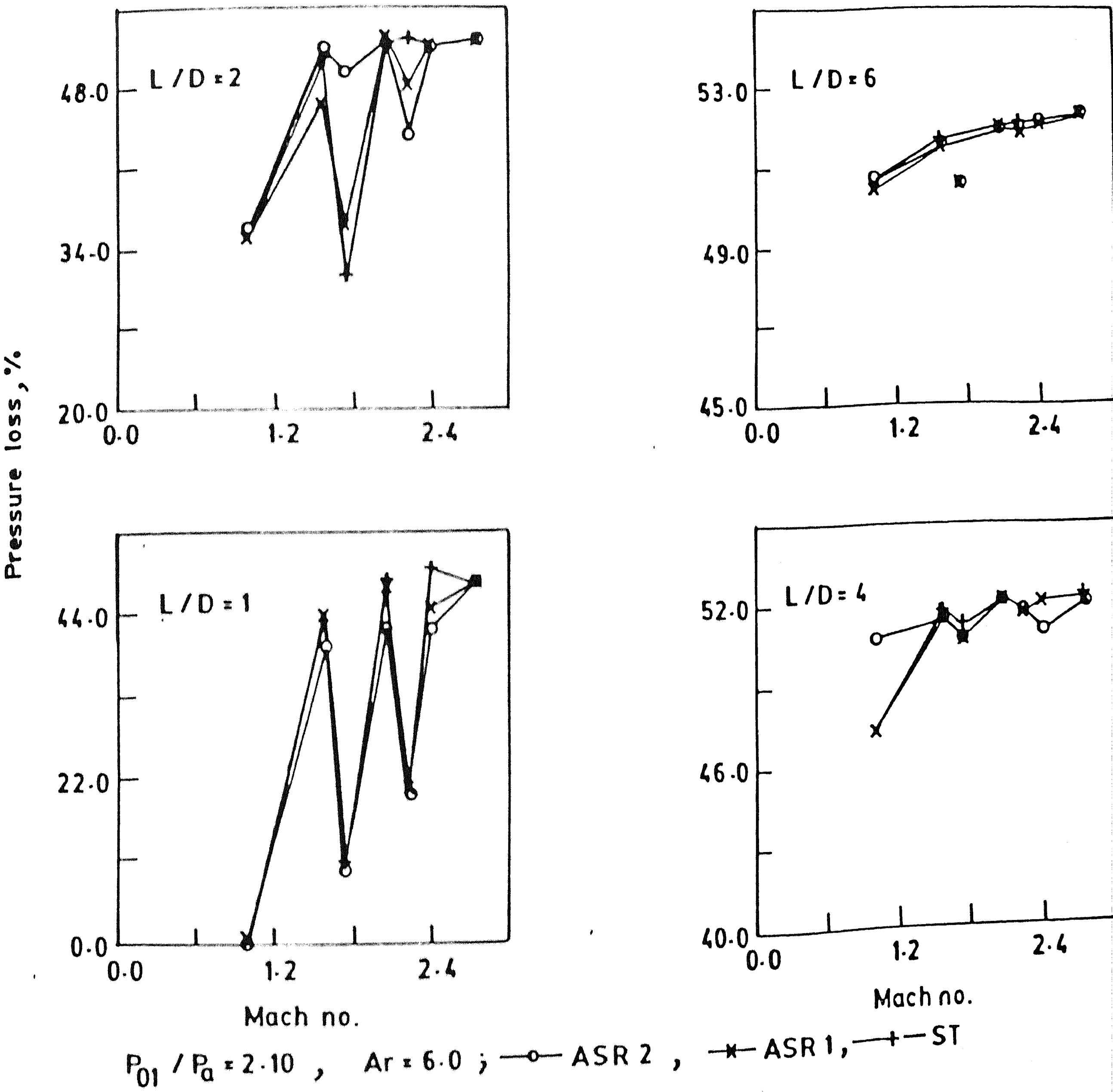


Figure 47: Pressure loss variation with Mach number

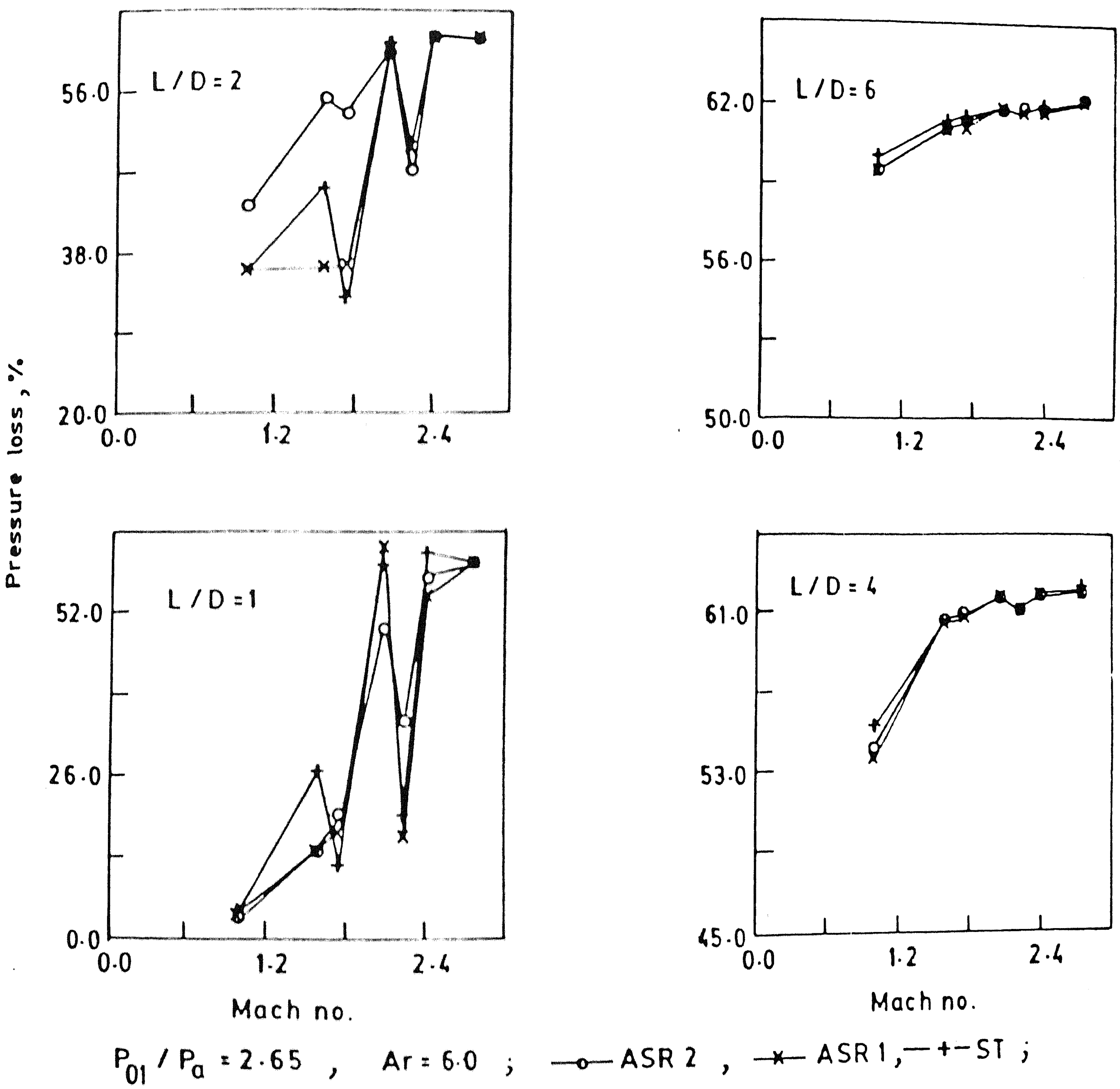


Figure 48: Pressure loss variation with Mach number

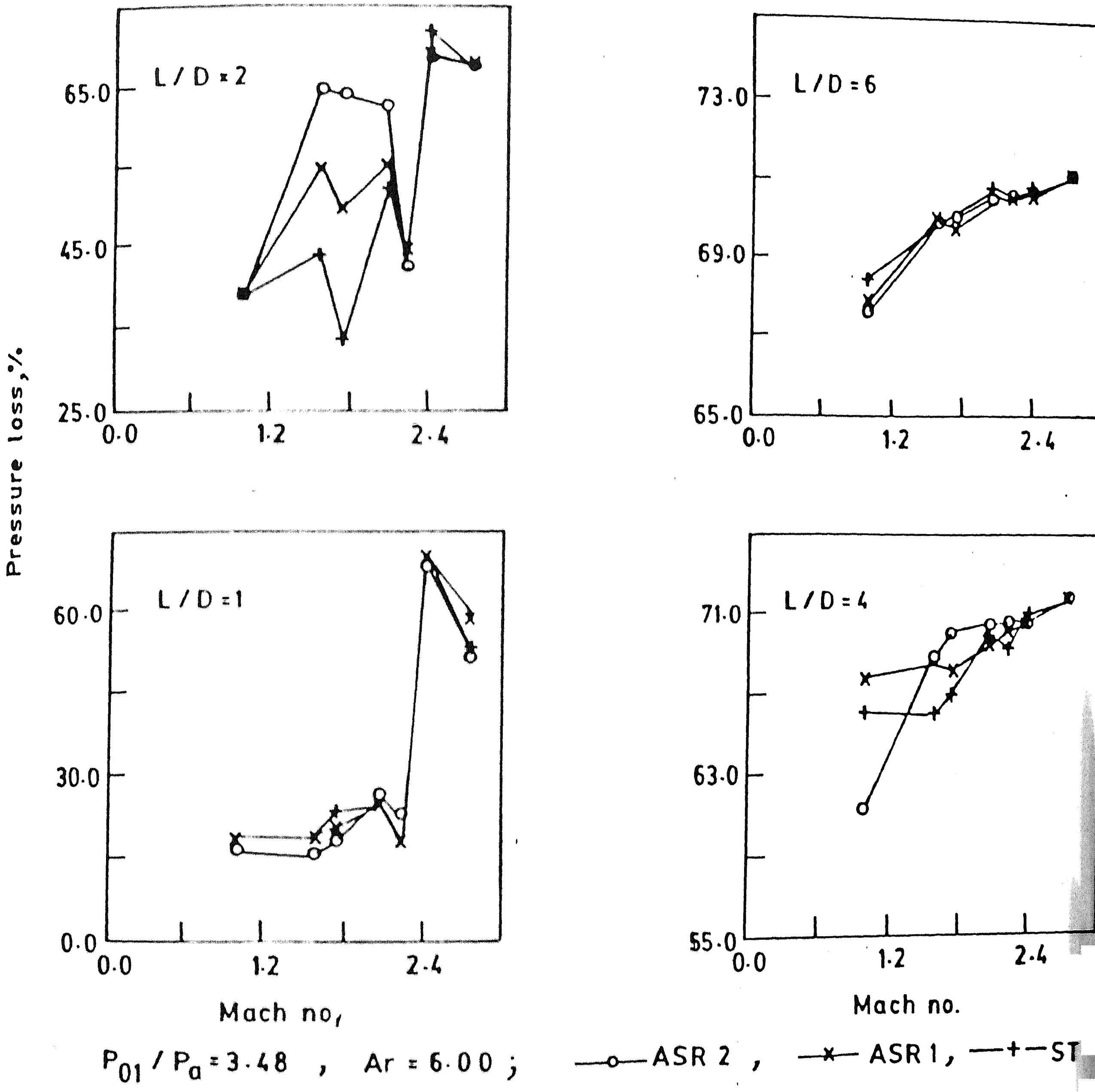


Figure 49: Pressure loss variation with Mach number

the cavities could be able to interfere with the flow considerably.

The pressure loss results for area ratio 2.89 given in figures 50 to 52 for the three values of the primary pressure ratios. Here it is seen that the effect of cavity as the pressure loss is predominant even for ducts with L/D more than 4. Again this domination increases with increase in primary pressure ratios, making the pressure loss to vary randomly with Mach number even for L/D more than 4. This can be clearly attributed to the reduced relief effects because of the low value of area ratio. Also, the secondary vortices generated by the cavities for this area ratio are in a position to have severe interactions with the main flow, thereby making the entire flow field upto the exit of the duct, oscillatory.

4.1.9 Variation of Pressure Loss with L/D Ratio

The results of measured pressure loss as a function of L/D are presented in Figures 53, 54 and 55. For area ratio 10 and 6, the pressure loss increases steeply from L/D 1 to 3 and then it assumes a constant value and becomes independent of L/D. This trend is common to all the primary pressure ratio of the present scheme. The cavity aspect ratio also does not have any effect on pressure loss for L/D more than 4 for the above area ratios at all the primary pressure levels. Even for L/D less than 3, the effect of cavity on pressure loss is only marginal for area ratios 6 and 10.

For area ratios 2.89, the pressure loss depends very strongly on L/D as well as cavity aspect ratio at all levels of primary pressures. However, the pressure loss increases drastically for L/D in the range from 1 to 6 and then slowly levels off to a constant value at L/D=10. The increase in cavity aspect ratio results in increase of pressure loss as the primary pressure increases for most of the runs made. However, there are some measurements resulting in smooth walled ducts experiencing less pressure loss compared with duct with annular cavity. This may

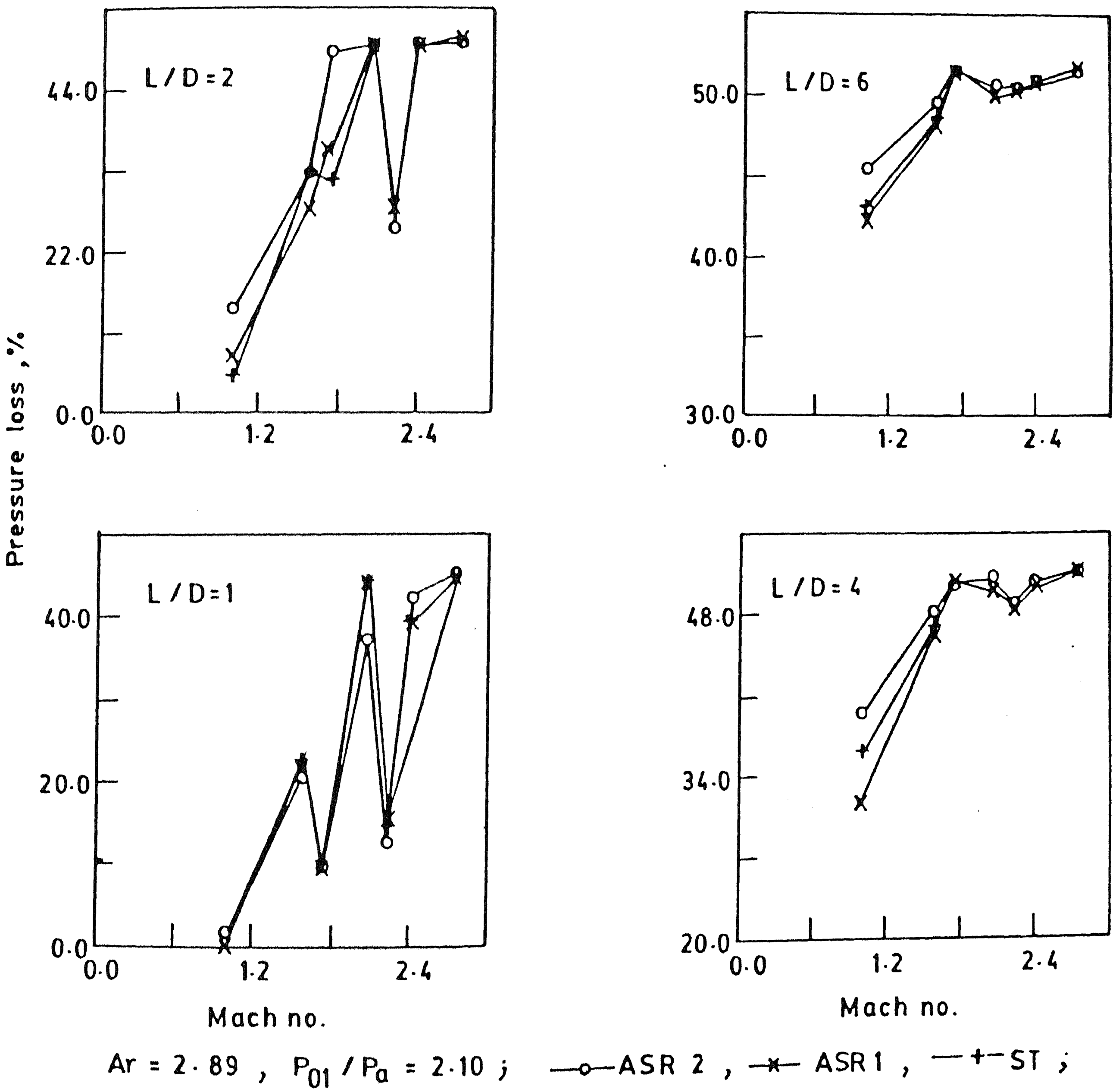


Figure 50: Pressure loss variation with Mach number

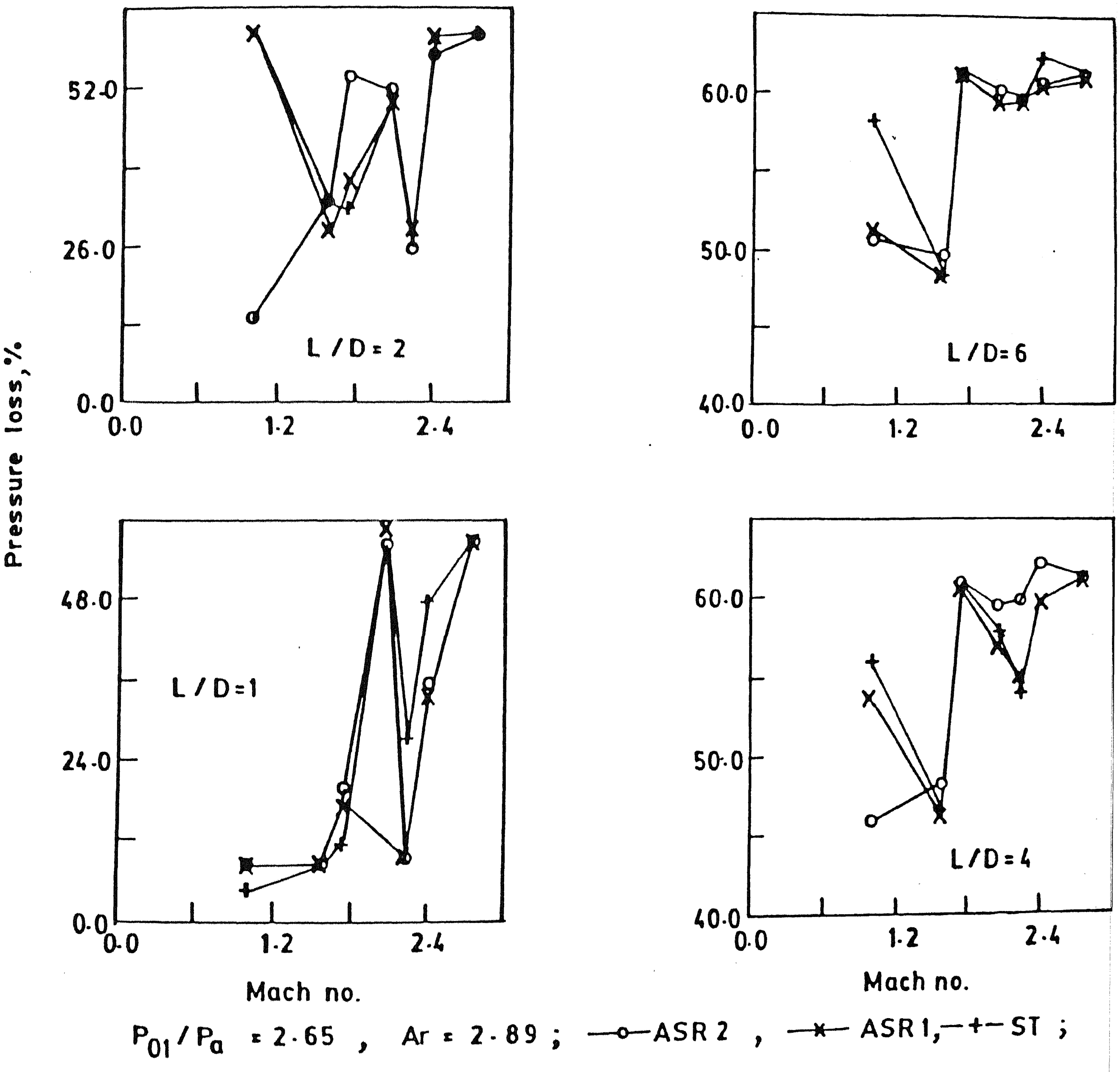


Figure 51: Pressure loss variation with Mach number

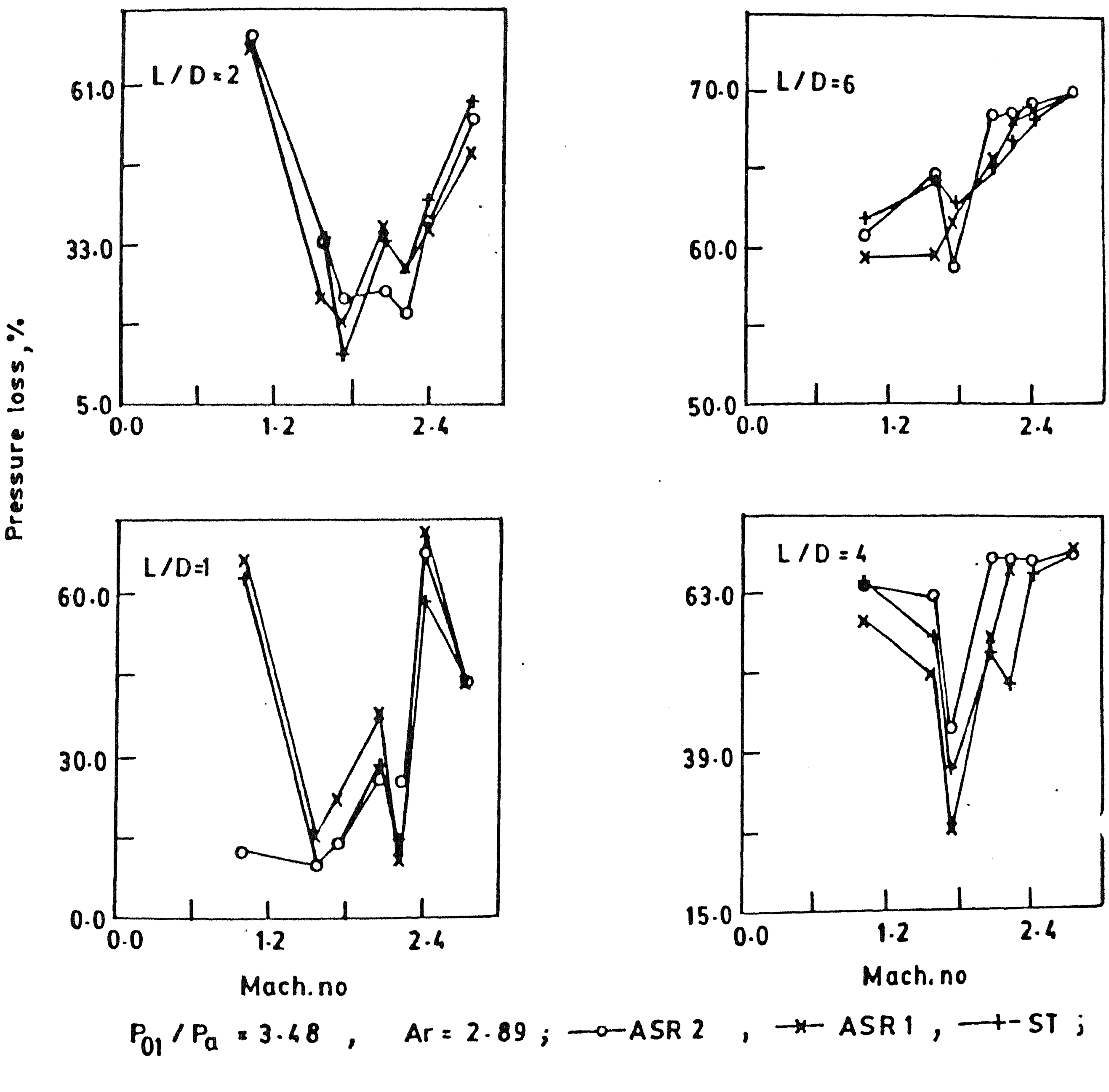


Figure 52: Pressure loss variation with Mach number

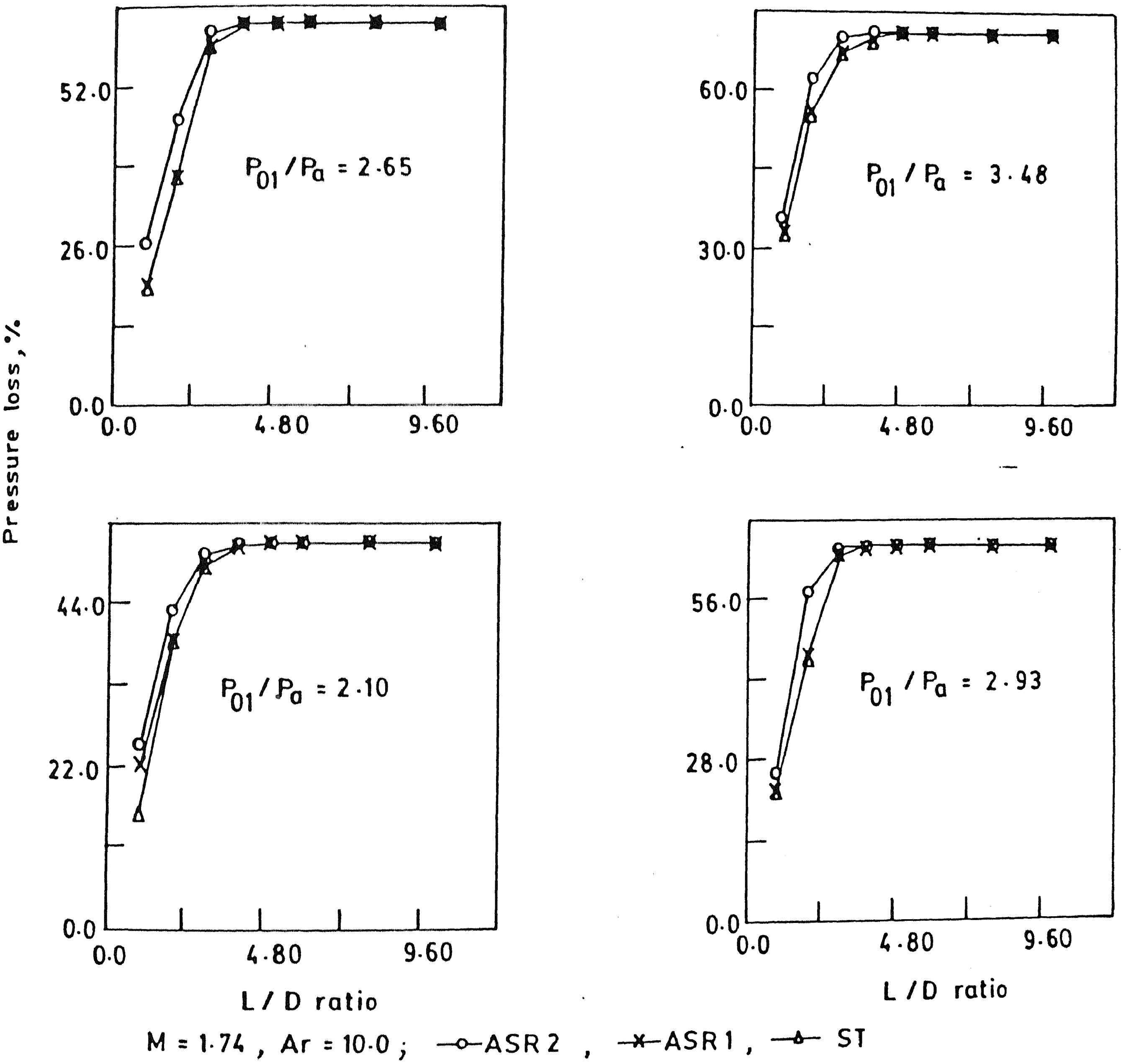


Figure 53: Pressure loss variation with L/D ratio

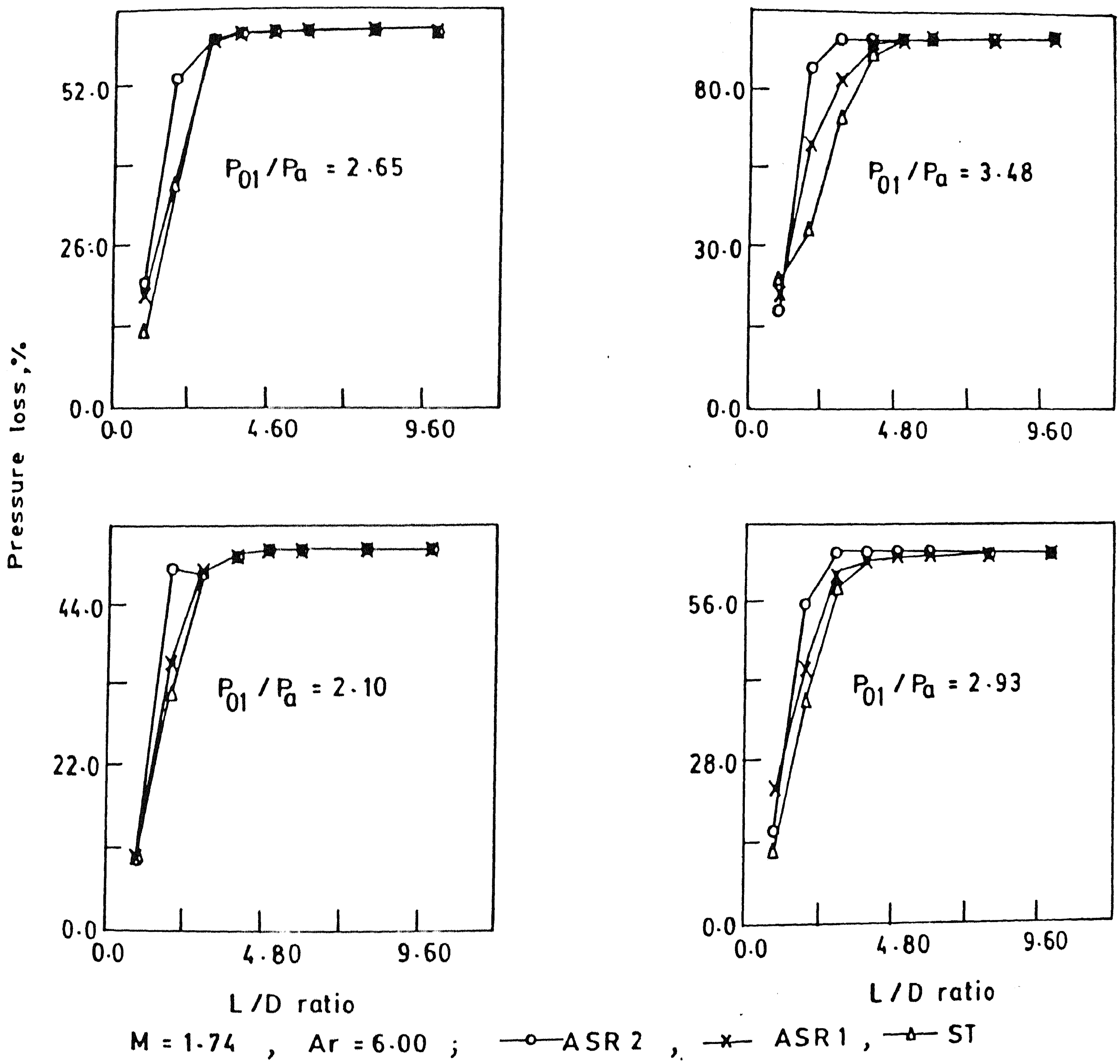


Figure 54: Pressure loss variation with L/D ratio

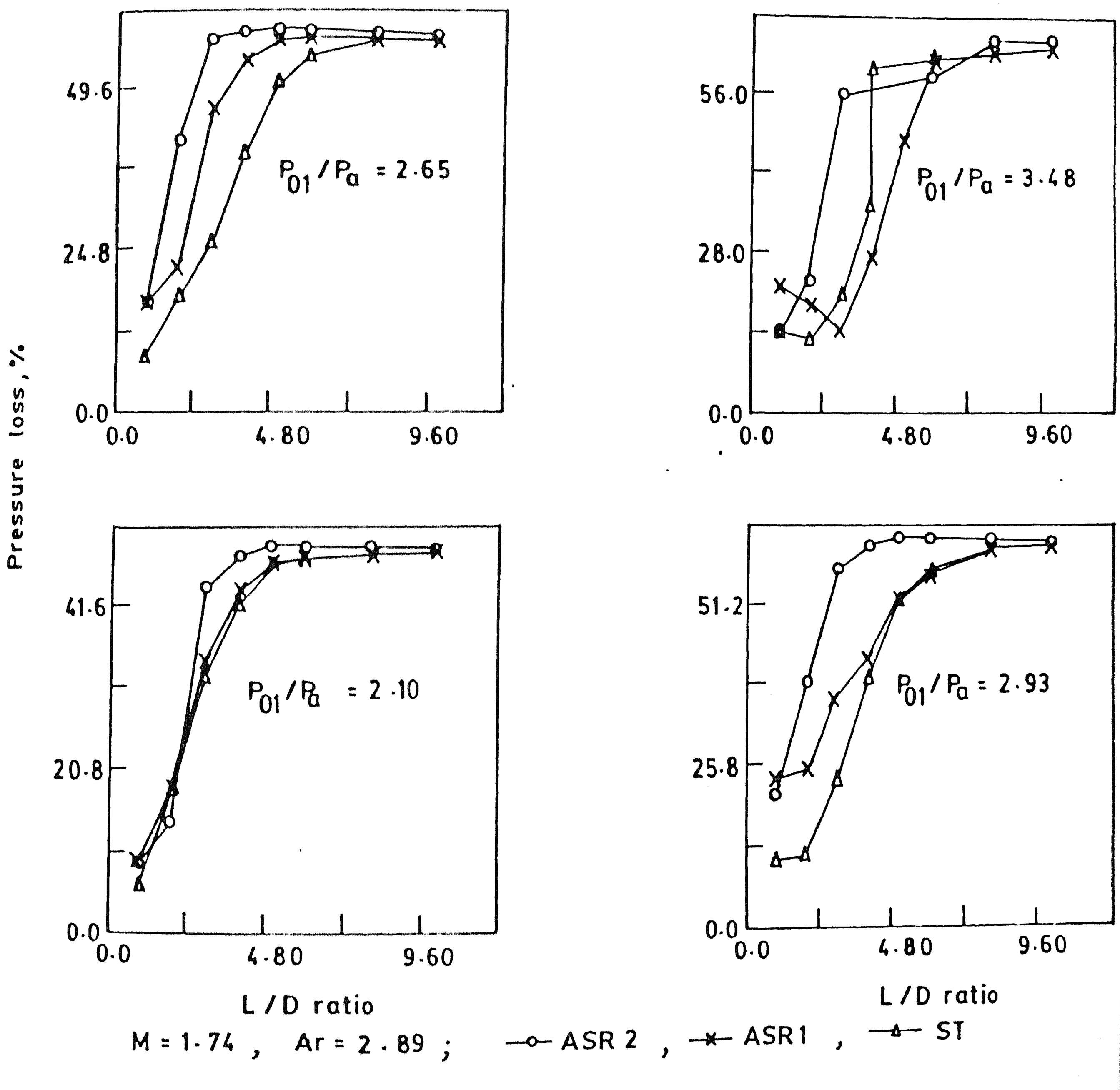


Figure 55: Pressure loss variation with L/D ratio

be due to measurement uncertainties since the pressure field was oscillatory and the mean value of the pressure was recorded as the representative value. But for this discrepancy, the smooth ducts always experienced lesser pressure loss compared to duct with annular cavities, as expected.

The cross plot of pressure loss with L/D for area ratios 2.89, 6 and 10 are shown respectively in figures 53, 54 and 55. It is seen from these results that there is drastic increase of pressure loss with L/D from 1 to 4. For L/D from 4 to 10, the pressure loss is only marginal as seen earlier. Further, the predominant effect of cavity aspect ratio on pressure loss for small values of L/D compared to it is longer values also seen from these results.

4.1.10 Variation of Pressure Loss with Primary Pressure Ratio

The measured pressure loss results as a function of primary pressure ratio are presented in figures 56, 57 and 58 for area ratios 10,6 and 2.89. From these results it is evident that for all the area ratios when the L/D ratio is less than 2, the pressure loss variation shows random nature with primary pressure ratio. However, for L/D more than 4, the pressure loss increases with primary pressure for area ratios 10 and 6. But for model with area ratio 2.89,the pressure loss does not follow any well defined order even for L/D more than 4. This again may be attributed to the restriction in the relief experienced by the small area ratio there by allowing the waves generated at the exit of the nozzle to dominate the entire length of the enlarged duct. Whereas for area ratios 6 and 10, the relief effect is considerable and the flow assumes proper order within few diameters since the L/D more than 4 is sufficient for such phenomenon to take place. Further it is observed that the order of pressure loss is more with increase in length of the passage as one can expect since in addition

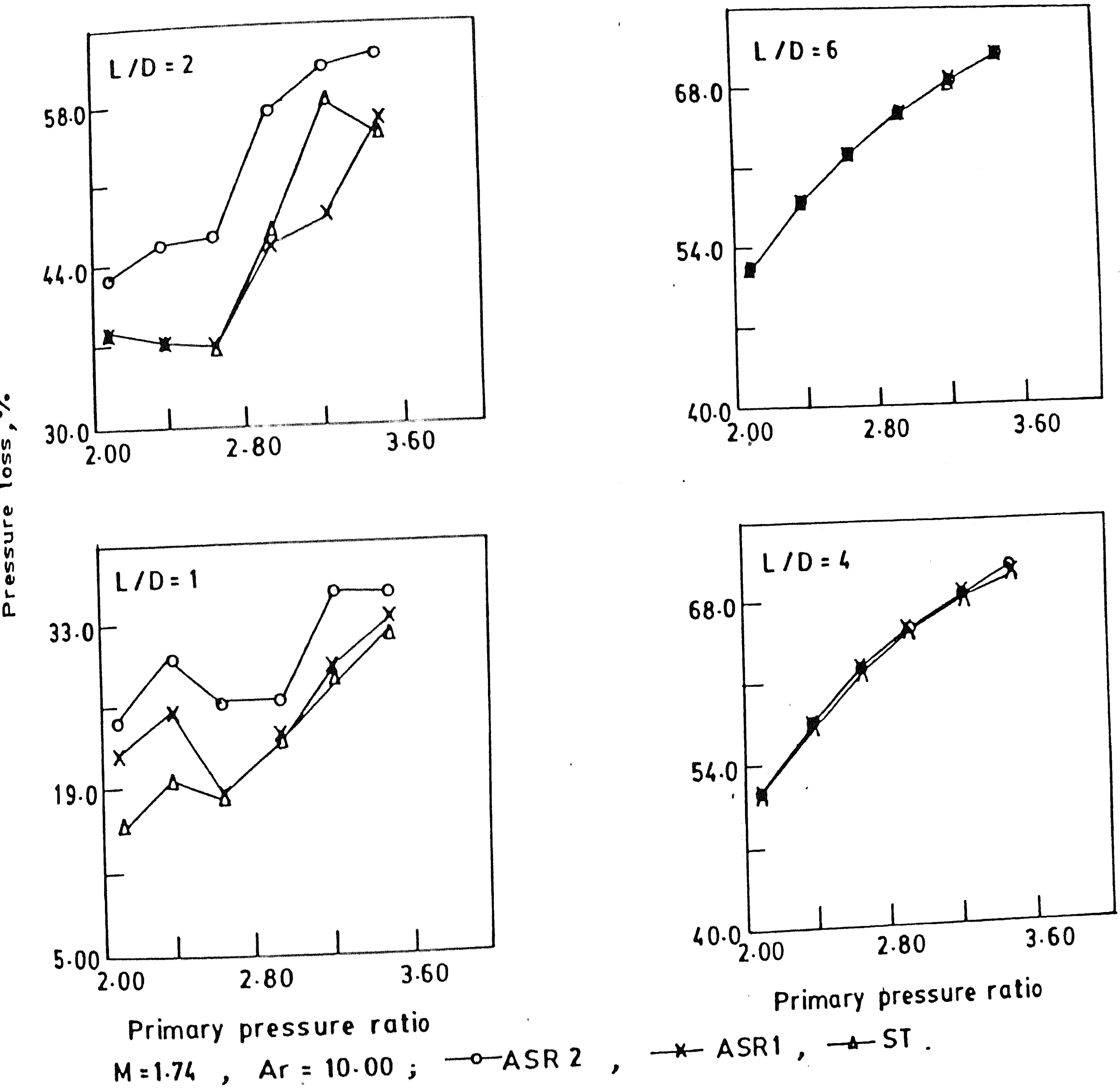


Figure 56: Pressure loss variation with primary pressure ratio

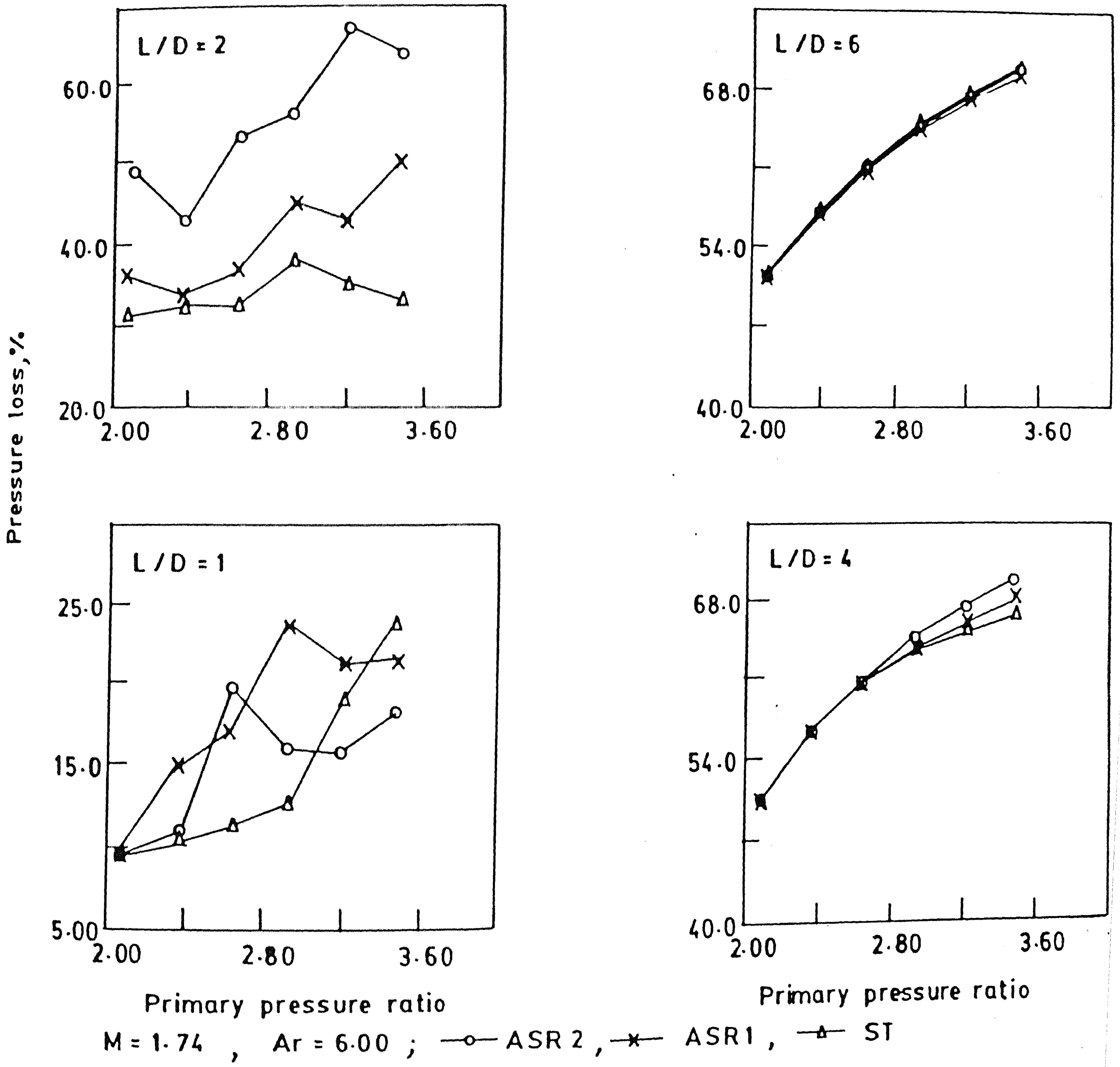


Figure 57: Pressure loss variation with primary pressure ratio

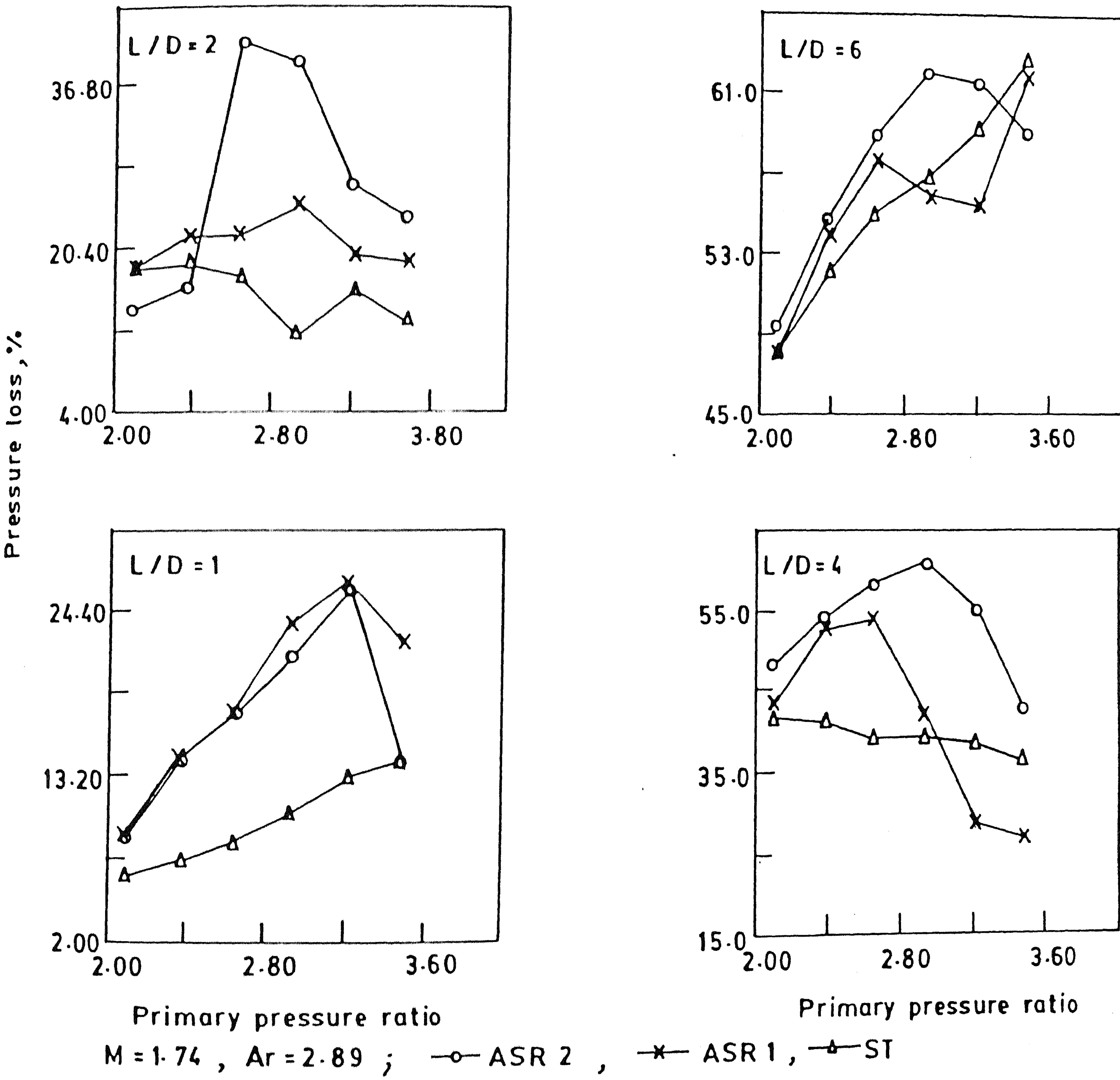


Figure 58: Pressure loss variation with primary pressure ratio

to the recirculating loss there are skin friction losses associated with the length of the passage when the flow expands in the enlarged duct. The present results even though for a particular nozzle exit Mach number of 1.74 they are representative of all the supersonic Mach numbers of the present experimental investigation.

The cavity aspect ratio has significant influence on the pressure loss at all lengths of the enlarged ducts for area ratio 2.89. However, for area ratios 6 and 10 the effect of aspect ratio is predominant for L/D upto 3 and it is only marginal for L/D more than 4.

4.1.11 Variation of Pressure Loss with Area Ratio

The cross plots of total pressure loss with area ratio at Mach 1.74 is presented in figures 59, 60 and 61 for primary pressure ratios 2.10, 2.65 and 3.48, respectively. Here again the phenomenon observed already for pressure loss is reiterated that is for L/D more than 4 the pressure loss for area ratio more than 6 is almost a constant with the cavity aspect ratio having little influence on them. However, at area ratio 2.89, the cavity aspect ratio influences the pressure loss significantly even at L/D 6 and above. For shorter lengths of enlarged duct in the range of L/D from 1 to 3 the pressure loss shows random variation with area ratio at all levels of primary pressure ratios.

4.2 Studies in Subsonic Regime

4.2.1 Variation of Base Pressure with Mach Number

The base pressure variation with Mach number in subsonic range for the three values of the model area ratios tested are presented in figures 62, 63 and 64. It is seen from these results that increase in Mach number results in monotonic decrease of base

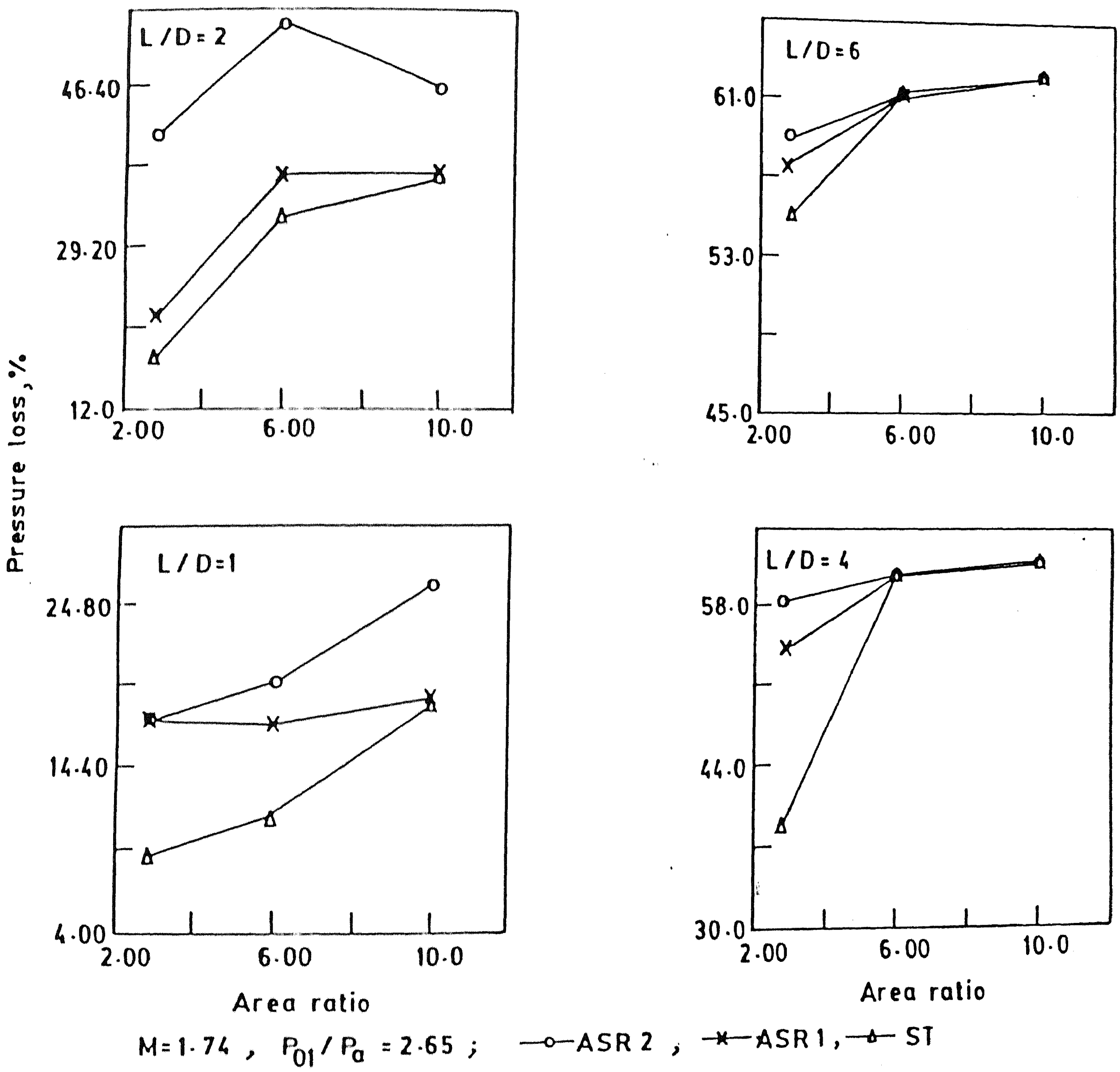


Figure 60: Pressure loss variation with area ratio

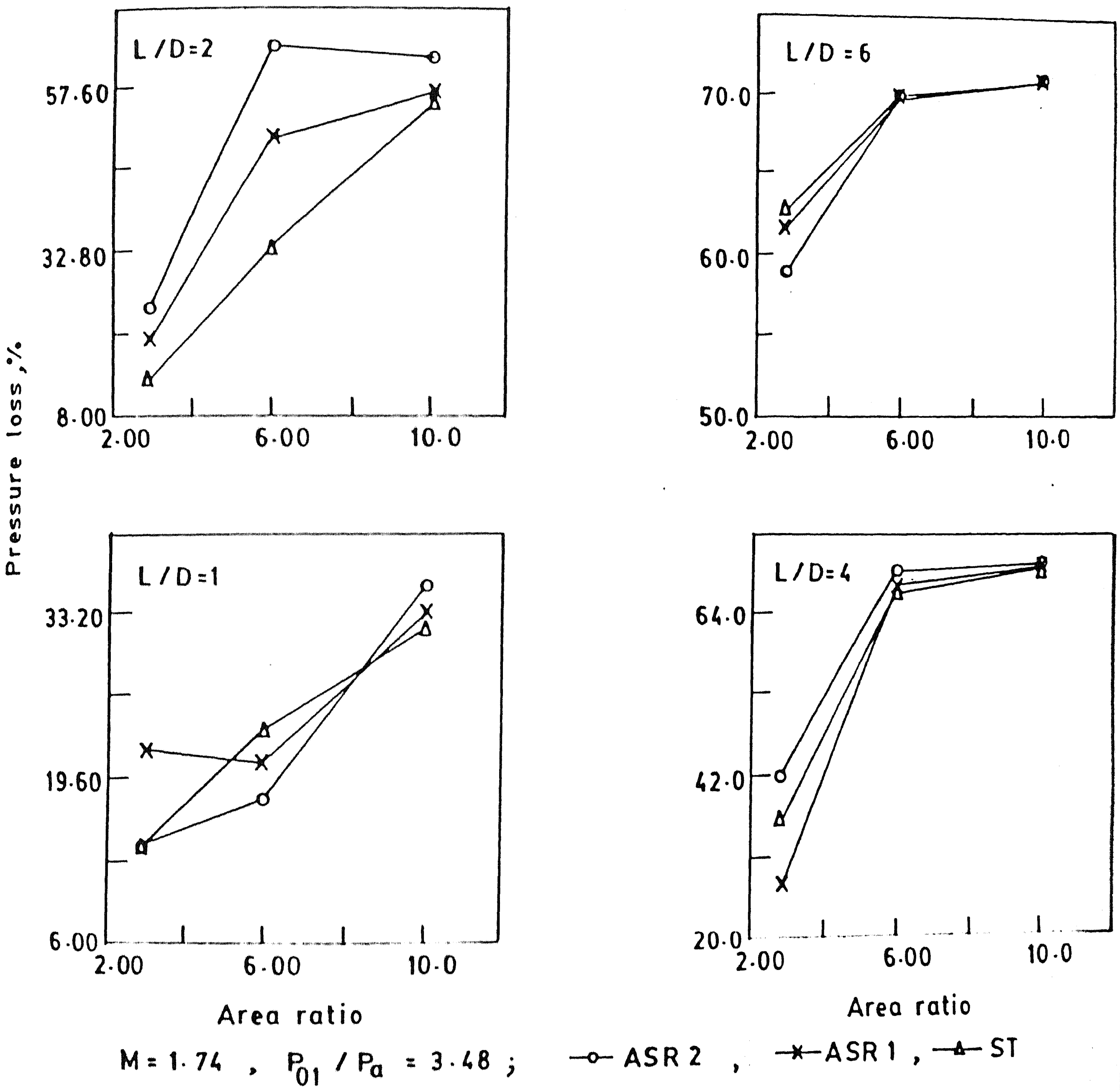


Figure 61: Pressure loss variation with area ratio

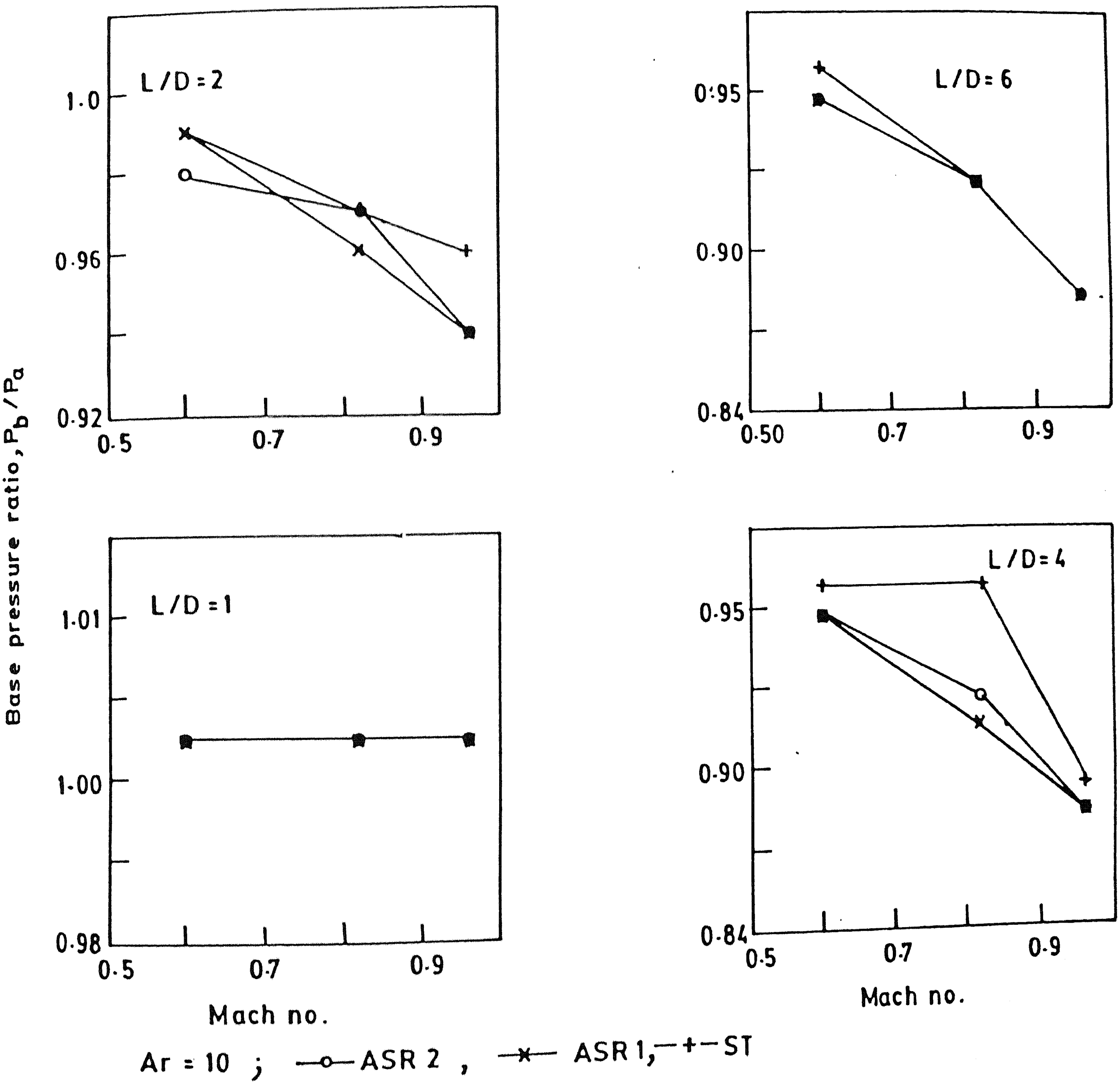


Figure 62: Base pressure variation with Mach number

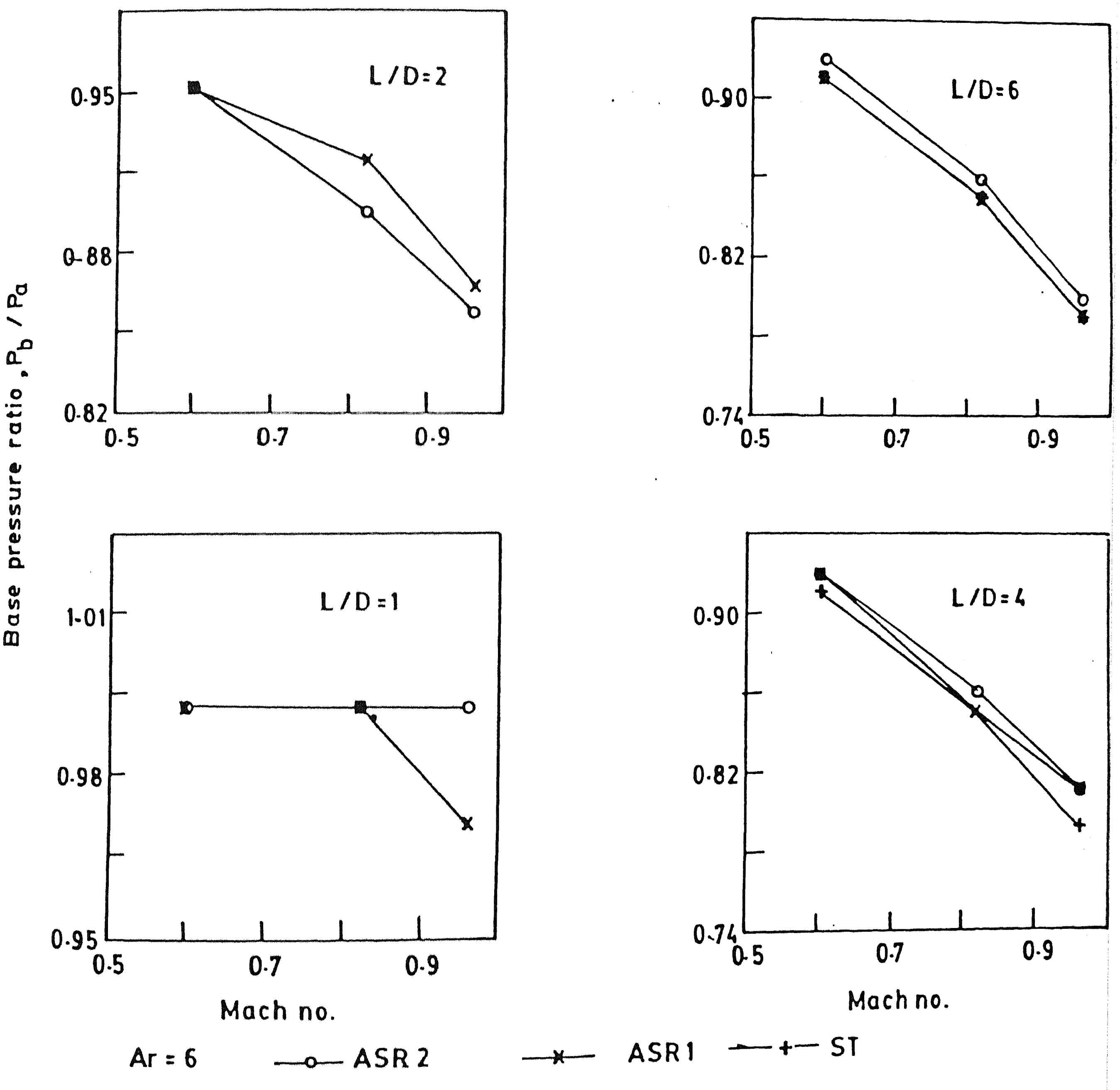


Figure 63: Base pressure variation with Mach number

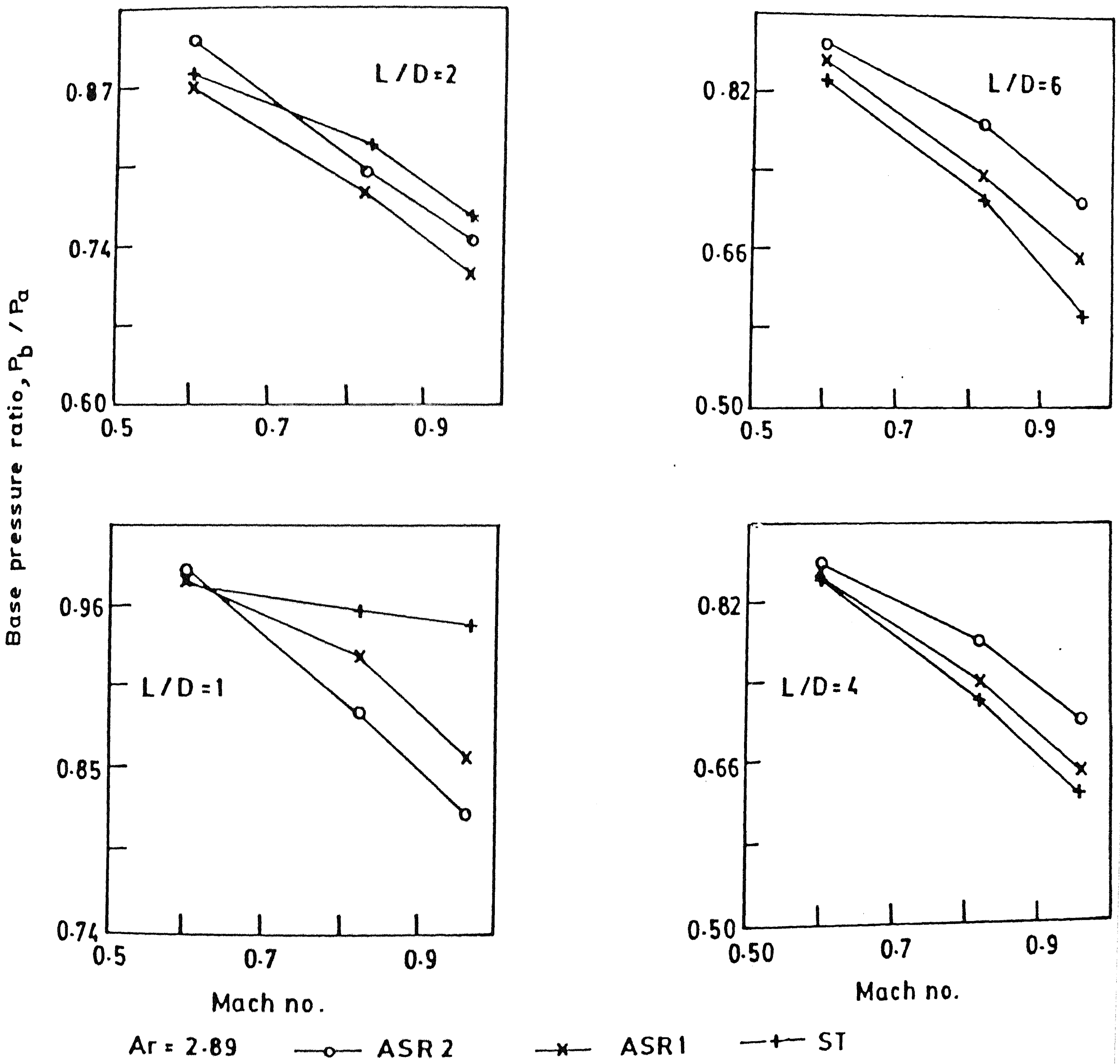


Figure 64: Base pressure variation with Mach number

pressure for all the three area ratios at all values of L/D. However, for L/D = 1, the effect of Mach number on base pressure does not assume any defined behavior. As discussed earlier, it is due to the fact that the enlargement length has to be more than a certain minimum for the flow expanding from the nozzle to get attached with the enlarged duct thereby forming a recirculating zone at the base, thereby influencing the base pressure. In the present range of paramenters, this minimum L/D seems to be 2. From here again, the Mach number increase resulting in decrease of base pressure is in very good agreement with the results of Rathakrishnan and Sreekanth [34]

4.2.2 Variation of Base Pressure with L/D Ratio

The base pressure results for subsonic Mach numbers are presented in figures 62 to 64. Figure 65 gives the variation of base pressure with enlargement length to diameter ratio for Mach 0.60 for the three area ratios tested namely 10, 6 and 2.89. Also, the variation of P_b/P_a with L/D for Mach 0.82 is given for area ratio 2.89 for comparison. From these results it is obvious that L/D more than 3 has got only marginal effect on the base pressure. Also base pressure assumes a minimum value at L/D about 5 to 6. This result is valid for all combinations of the parameters of the present study. Even though the cavity influences the base pressure for L/D more than 3, the fact that base pressure assumes a minimum for L/D in the range 5 to 6 is not affected by the cavity aspect ratio. This trend of drastic decrease in base pressure for L/D from 1 to 3 and base pressure attaining a minimum for L/D around 5 is in excellent agreement with the results reported by Rathakrishnan and Sreekanth [34], and Rathakrishnan et al [60]. Further it is seen from this figure that Mach number has got very strong influence on the base pressure making it to decrease with increase of Mach number. Further the cavities make the base pressure

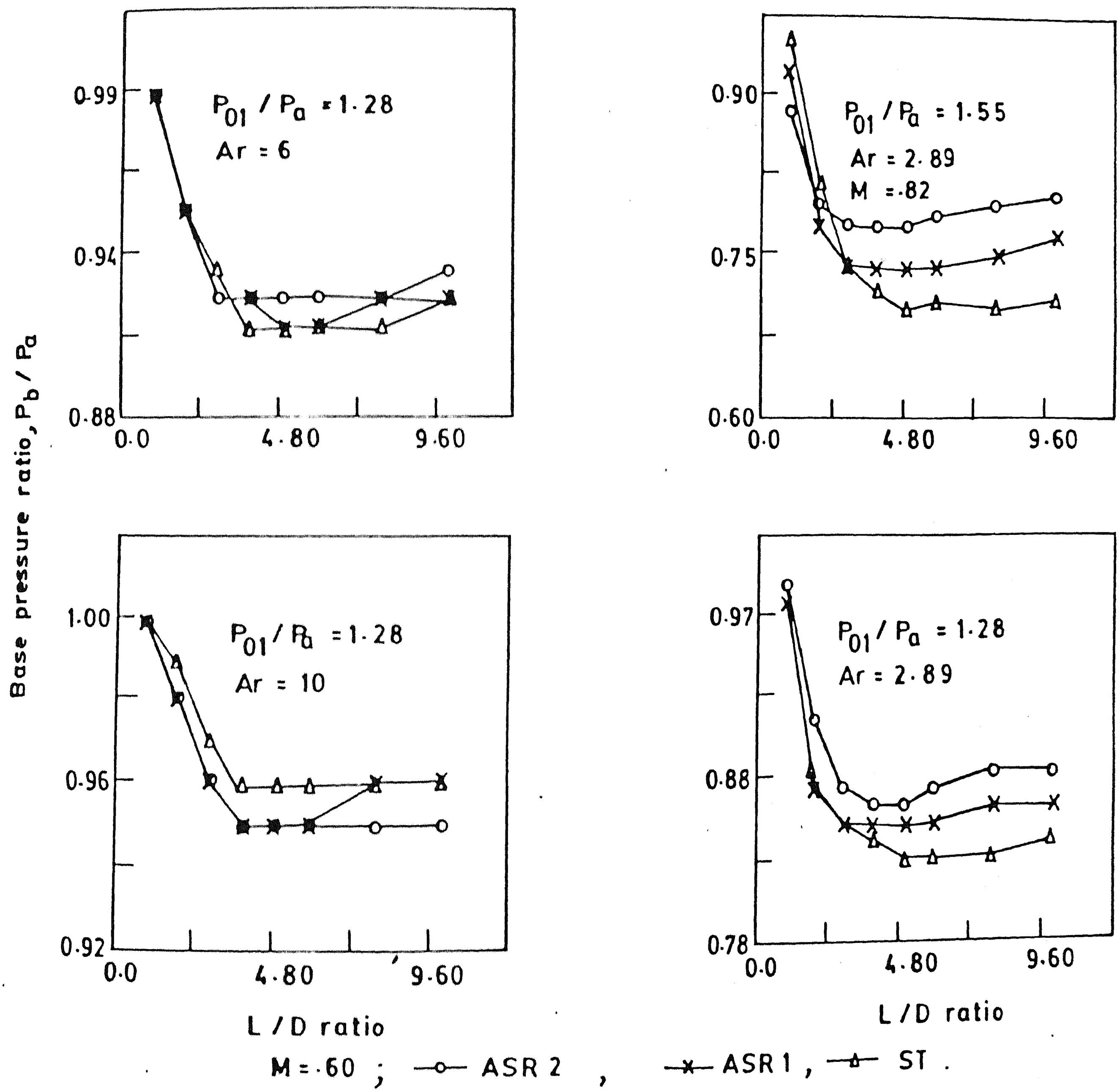


Figure 65: Base pressure variation with L/D ratio

to assume higher values at all values of L/D.

4.2.3 Variation of Base Pressure with Area Ratio

The cross plot of base pressure with area ratio is shown in figure 66 for Mach number 0.60. It is obvious from these results that increase in area ratio results in increase of base pressure as one could expect. Once again the effect of L/D on the base pressure is also seen from these results.

4.2.4 Variation of Wall Pressure Along the Enlarged Duct

The well static pressure in the enlarged duct for nozzle exit Mach number of 0.60 are presented for all the three area ratios of the present study in figures 67, 68 and 69. The effect of the annular cavity is also shown on these figures. The results for subsonic flow shows a trend which is completely different from that for supersonic flows. That is for a plane duct without annular grooves the flow development from base region to duct exit shows an oscillatory nature. Whereas for ducts with cavity the oscillatory nature is suppressed considerably. Further the increase in cavity aspect ratio seems to increase the suppression effect thereby making the flow to expand smoothly form base pressure level to almost atmospheric at the duct exit. These results are in very good agreement with the results of Rathakrishnan et al [60]. Here again, is obvious from these results that the duct should have a definite minimum length for the flow from the nozzle to get attached and develop. Like in the case of supersonic Mach numbers the length of the duct required for proper flow development is around 4 times the diameter. One more result of interest from these plots is that the increase in the relief effect due to increase of area ratio seems to enhance the oscillatory nature of the flow considerably.

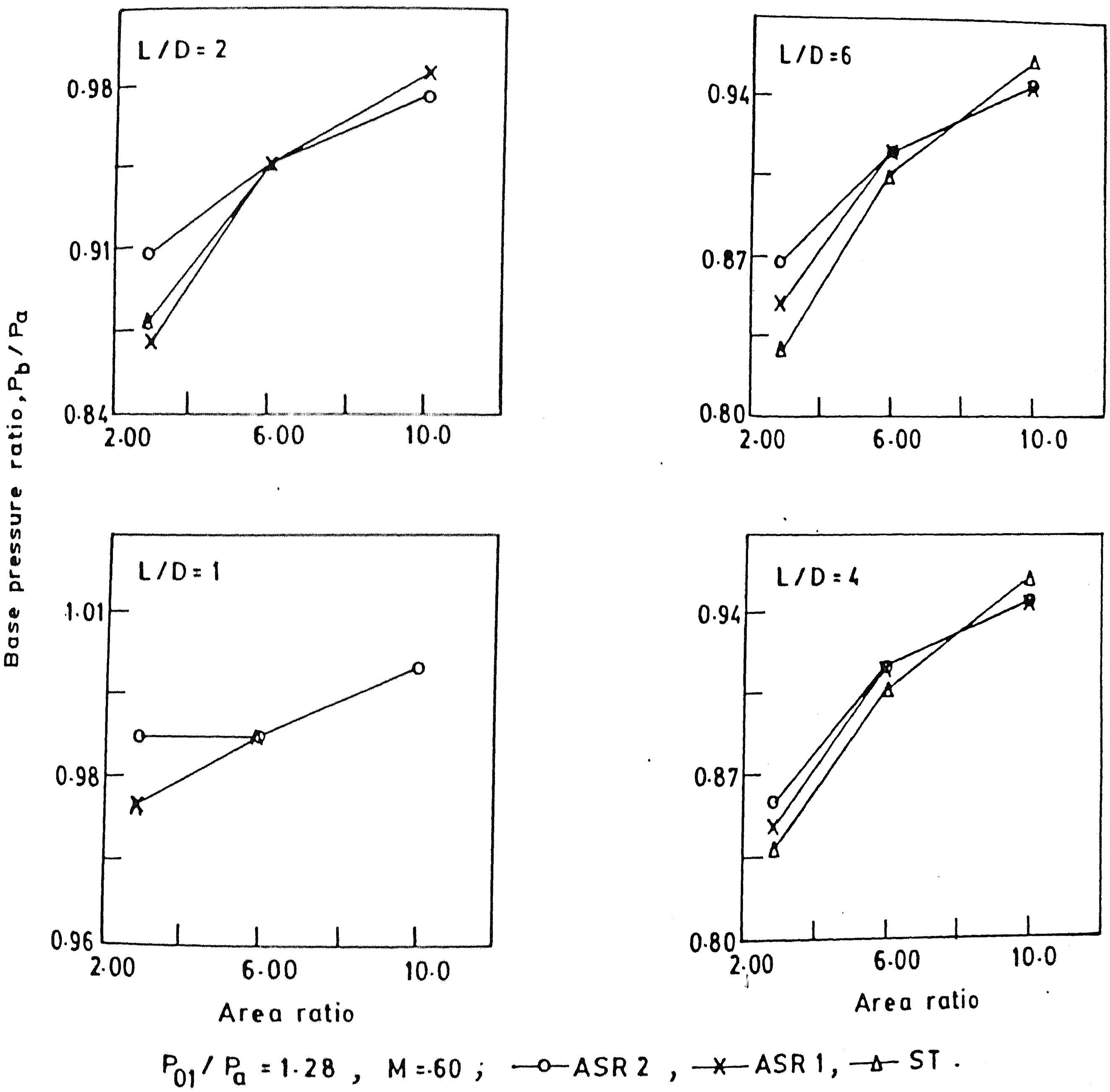


Figure 66: Base pressure variation with area ratio

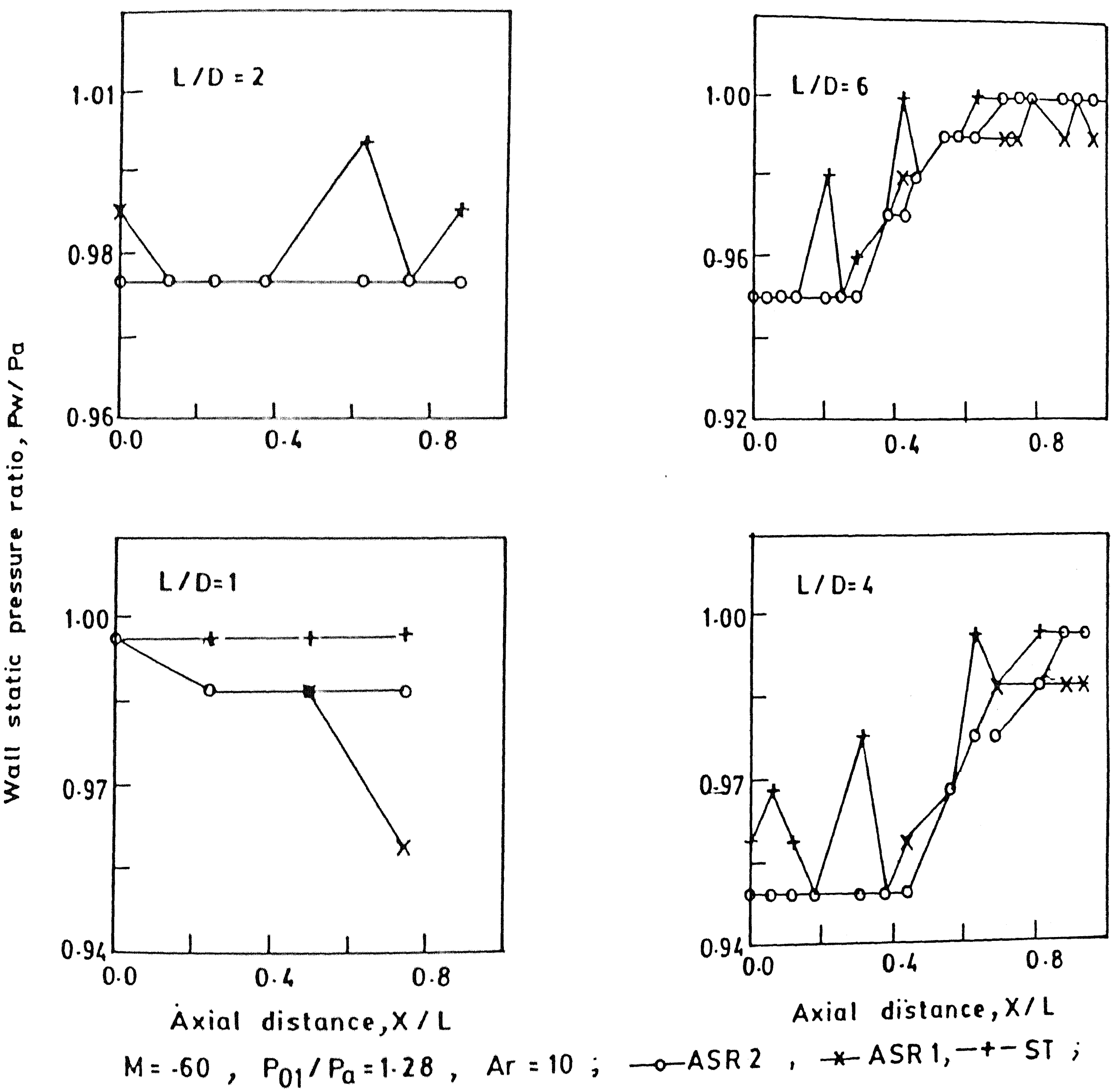


Figure 67: Wall pressure variation with X/L

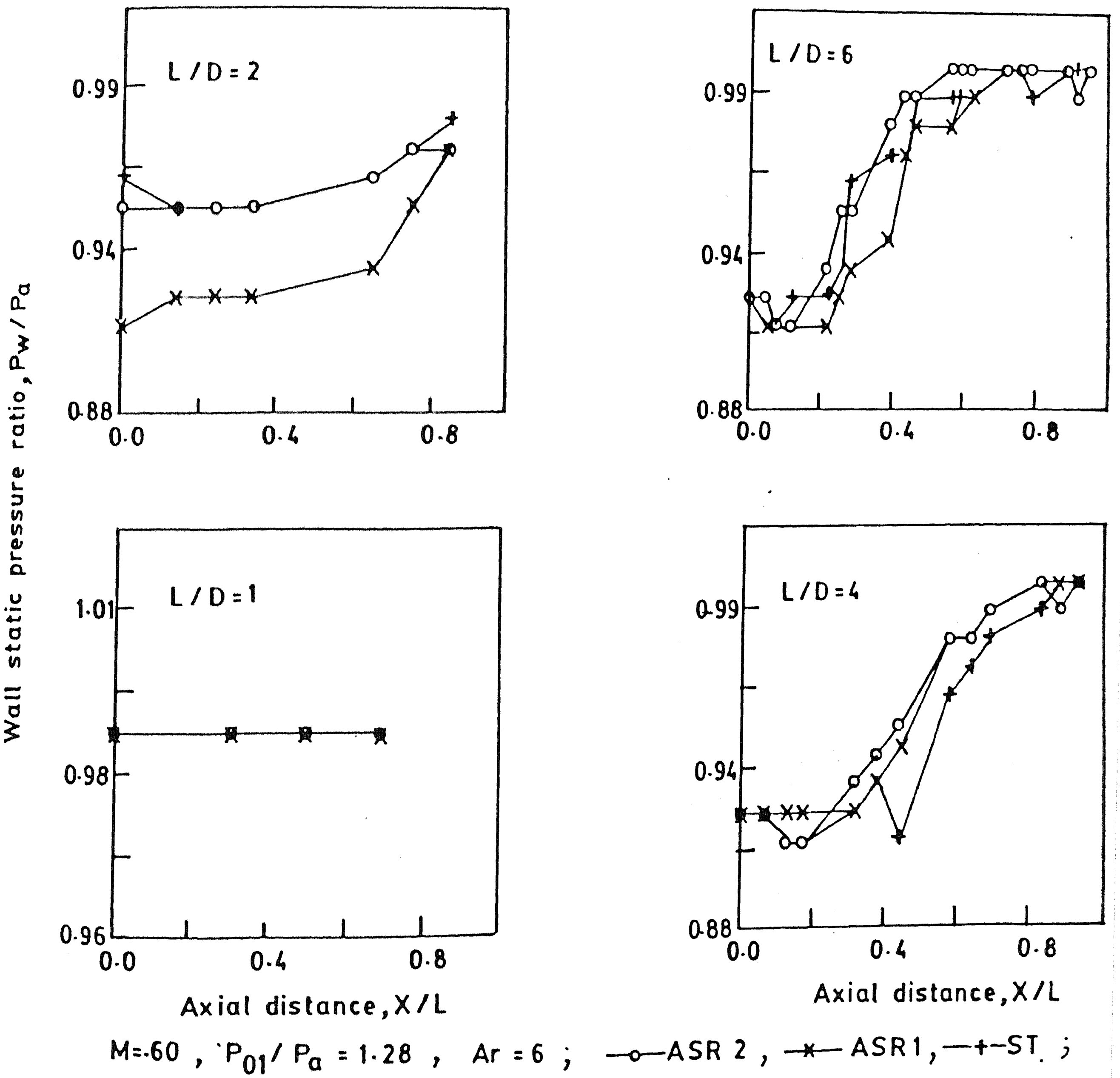


Figure 68: Wall pressure variation with X/L

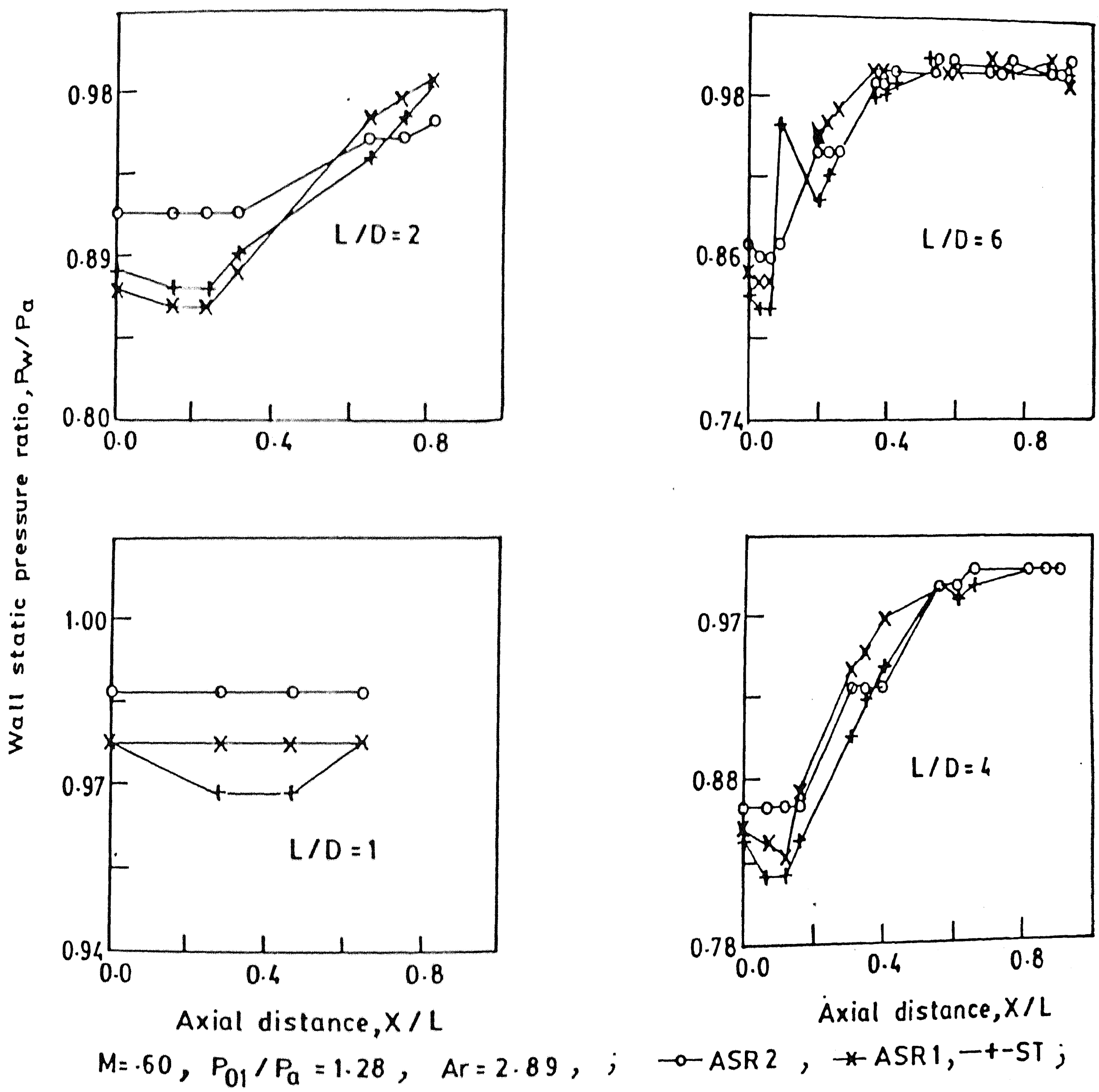


Figure 69: Wall pressure variation with X/L

4.2.5 Variation of Pressure Loss with Nozzle Exit Mach Number

The effect of Mach numbers in the subsonic range on the total pressure loss is shown in figures 70, 71 and 72. Increase in Mach number results in increase of pressure loss, as expected. For all the area ratios the increase of pressure loss with Mach number is almost linear for L/D more than 4 at all area ratios. However, for small values of L/D in the range less than 2 there is no defined pattern of pressure loss variation with Mach number.

4.2.6 Variation of Pressure Loss with L/D Ratio

The results of pressure loss in subsonic range of the nozzle exit Mach numbers are presented in figure 73, as a function of L/D and cavity aspect ratio. The pressure loss shows a trend which is directly opposite of base pressure behavior with L/D. The presure loss increases drastically with L/D for L/D from 1 to 4 and then assumes almost a constant value. In the present flow system, the pressure loss is due to the vortices and the skin friction. At Mach 0.60, it is seen that area ratio 6 and 10 experience maximum pressure loss of 20% where as the maximum loss for area ratio 2.89 is 18%. The cause for this could be the following:

Even though the vortices at the base zone of area ratio 2.89 is stronger than those for area ratio 6 and 10, the flow has to pass through a larger surface area before exiting the duct for area ratio 6 and 10 compared to 2.89. Therefore, for the case of 2.89 area ratio even though loss due to vortices is more than that for area ratios 6 and 10, the skin friction loss should be much less than that in the ducts with area ratios 6 and 10, thereby making the flow in the larger ducts to experience more pressure loss compared to the flow through the smallest one.

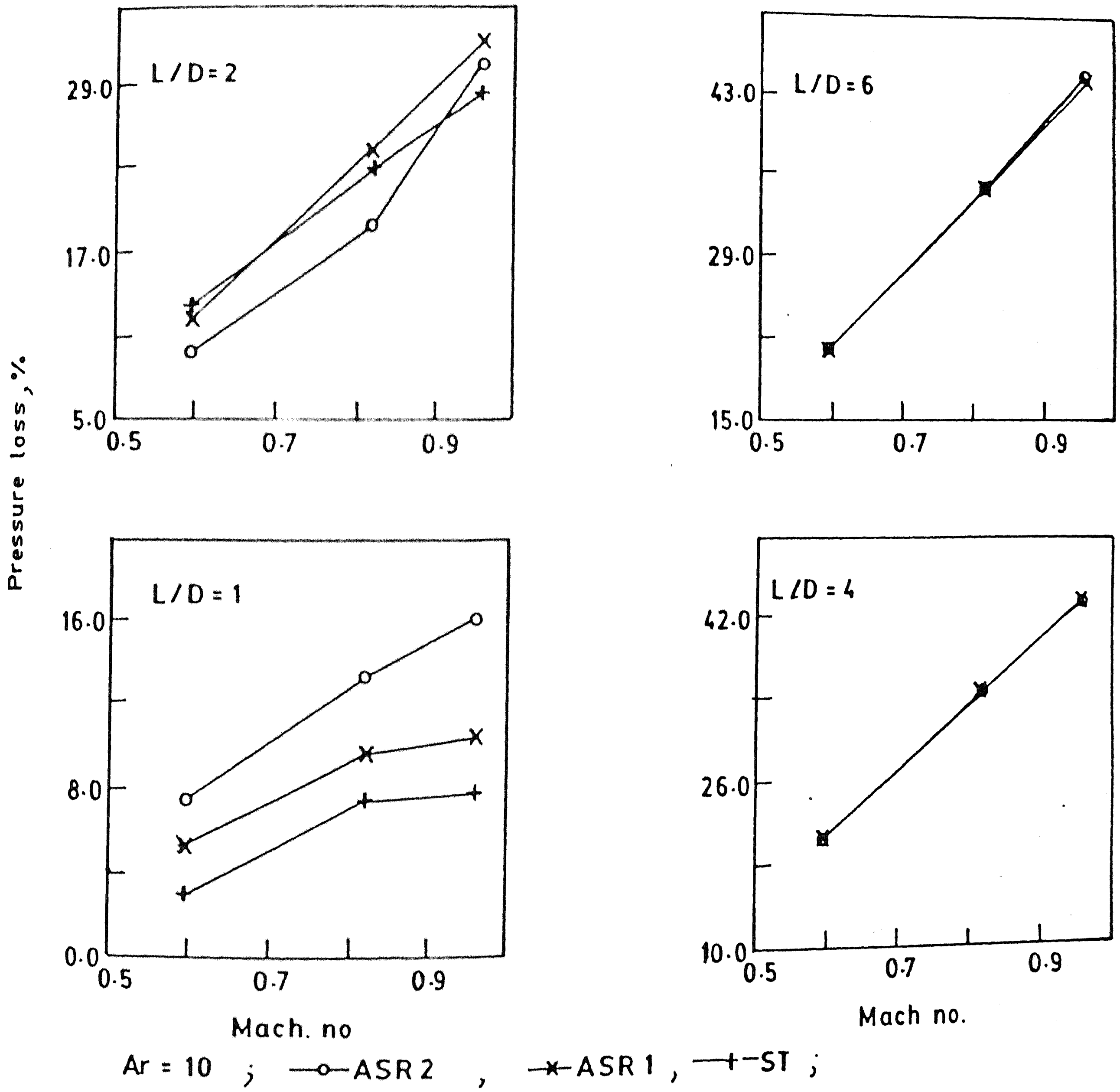


Figure 70: Pressure loss variation with Mach number

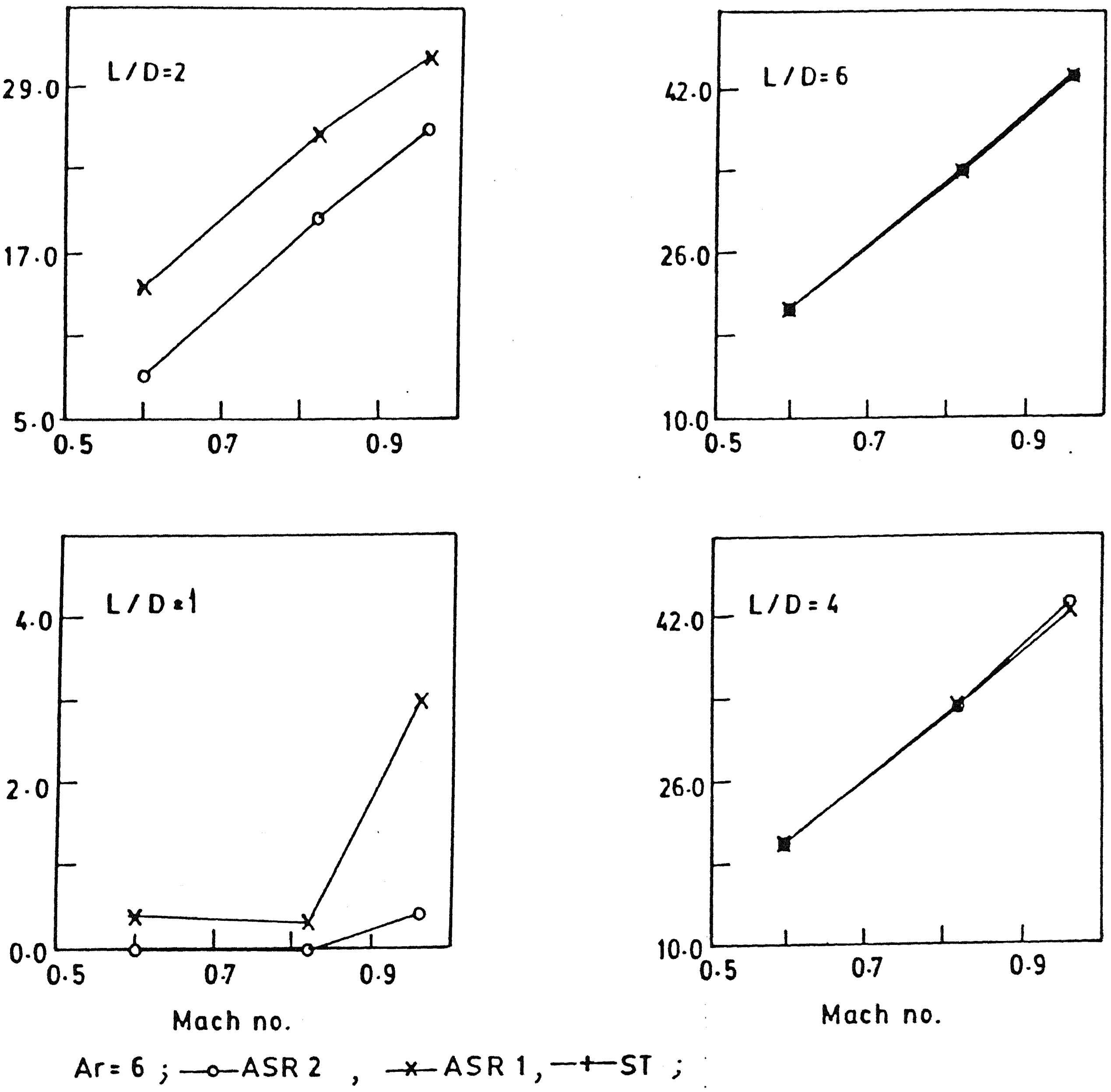


Figure 71: Pressure loss variation with Mach number

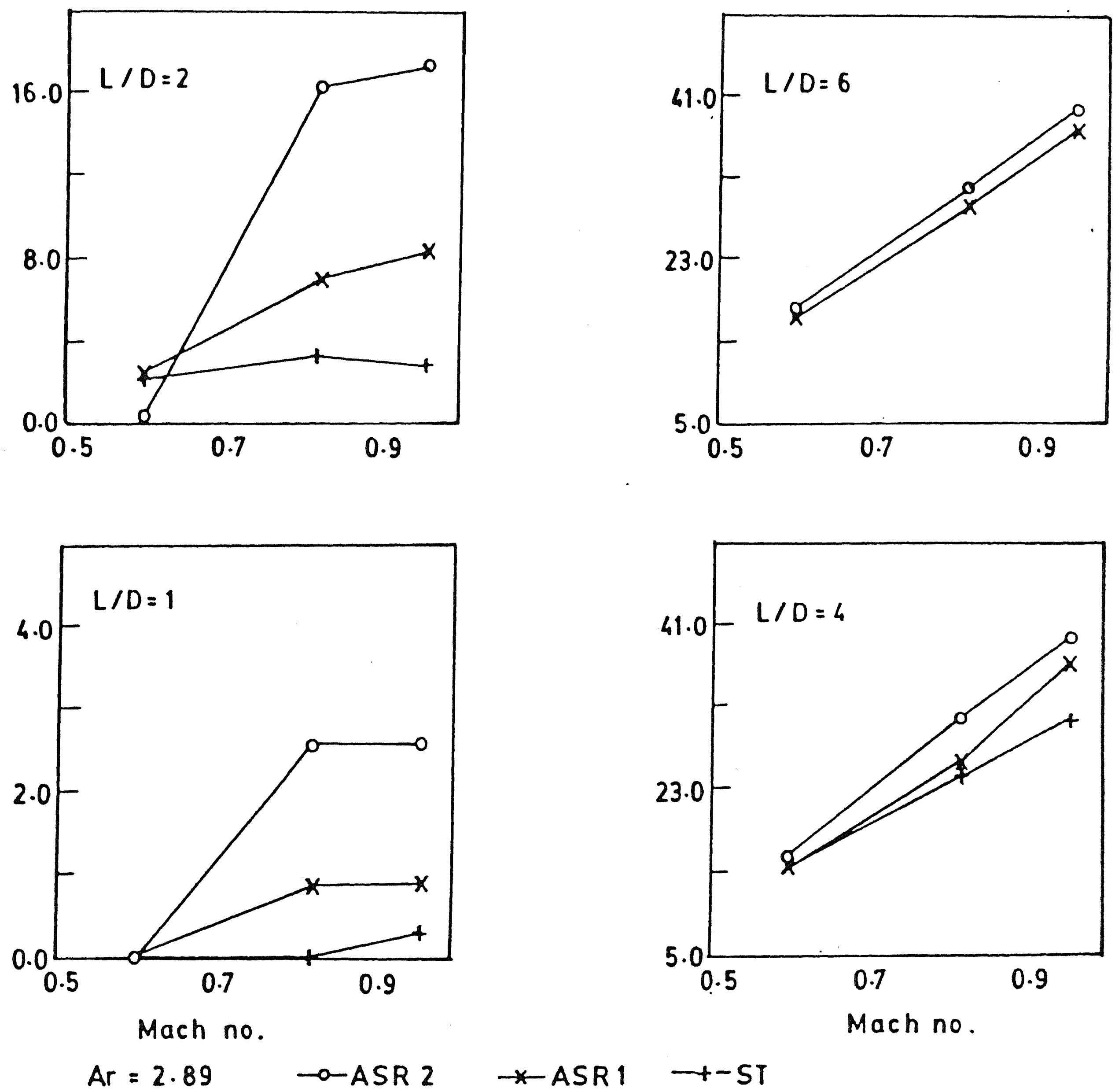


Figure 72: Pressure loss variation with Mach number

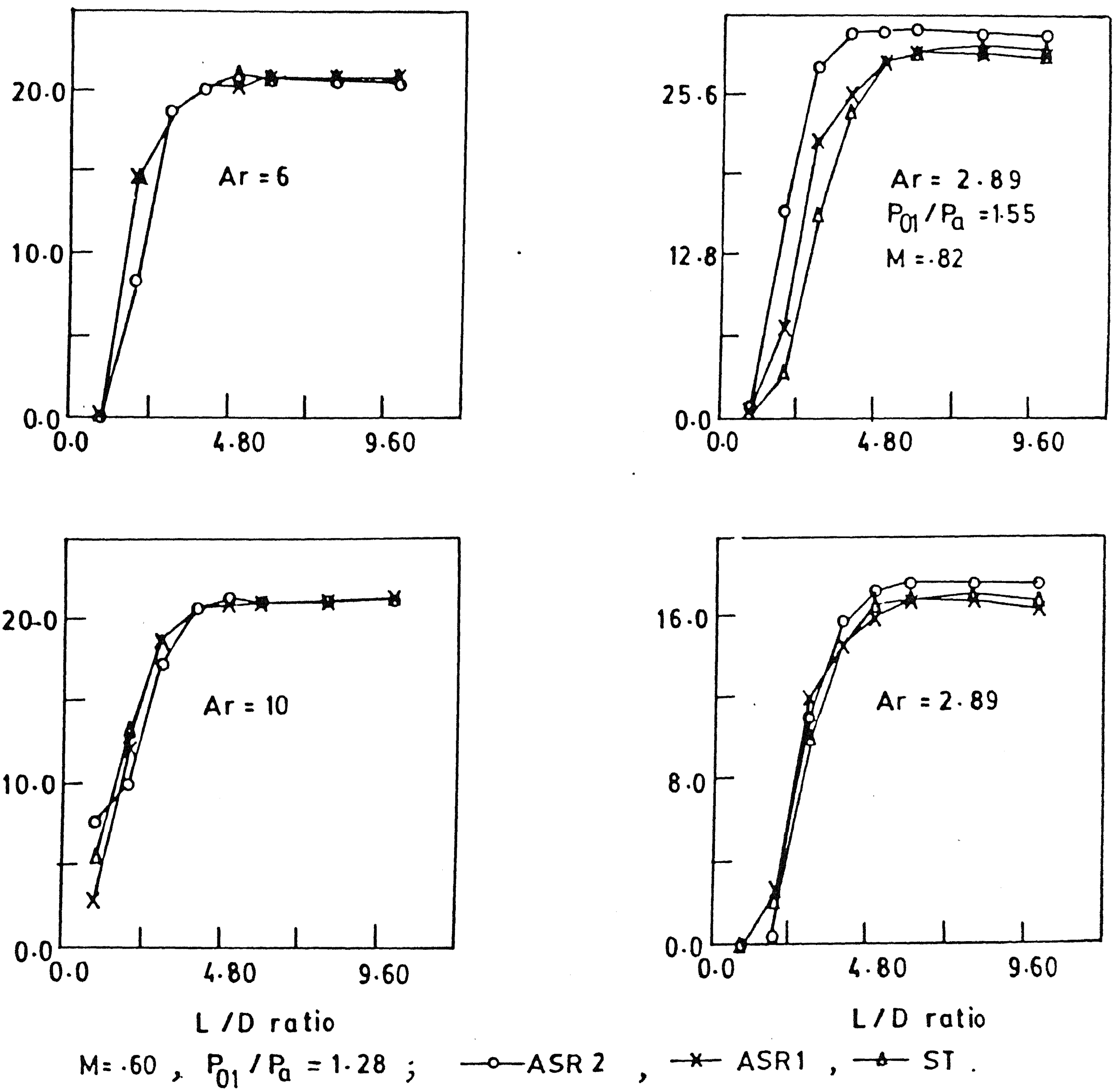


Figure 73: Pressure loss variation with L/D ratio

The Mach number has got very strong influence on the pressure loss as it is seen from the comparison of the results for Mach 0.60 and 0.82 for area ratio 2.89. It is seen that increase of Mach number from 0.60 to 0.82 results in drastic increase in pressure loss from nearly 18% at Mach 0.60 to nearly 31% at Mach 0.82. This is due to the fact that both the loss due to vortices and due to skin friction increases with increase in Mach number in the subsonic region.

4.2.7 Variation of Pressure Loss with Area Ratio

The pressure loss variation with area ratio for Mach 0.60 is presented in figure 74. The pressure loss shows steep rise for area ratios from 2.89 to 6 and then it increases marginally from area ratios 6 to 10 for L/D more than 4. However, for small values of L/D, since the flow from the nozzle is not in a position to get attached with the duct wall and proceed downstream, the pressure loss variation with area ratio does not show any defined trend.

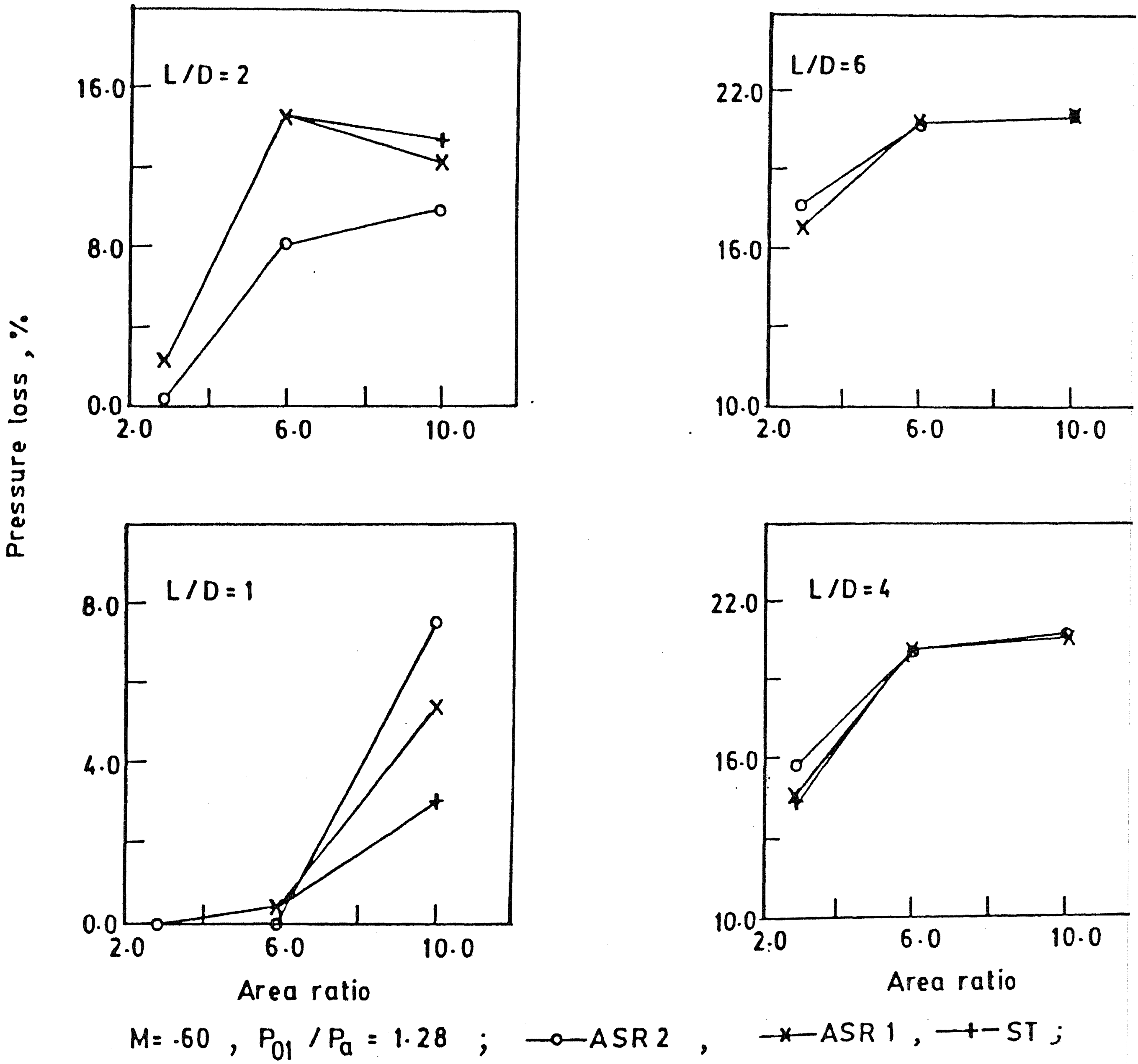


Figure 74: Pressure loss variation with area ratio

Chapter 5

SUMMARY AND CONCLUSIONS

From the results and discussions of the present experimental investigation presented in the previous chapter, the following are the main conclusions drawn.

1. The base pressure is strongly influenced by the geometrical parameters *viz.* the area ratio of the passage, the length to diameter ratio of the enlarged duct and also by the nozzle exit Mach number. The effect of annular cavity on base pressure is only marginal.

2. The base pressure is found to be oscillatory for flow from convergent–divergent nozzles, whereas, for flow from Laval nozzles the oscillations are almost insignificant. It is also insignificant for the flow from convergent nozzle.

3. The annular cavities are found to increase the base pressure with increase in their aspect ratio for subsonic Mach numbers. However, for supersonic Mach numbers the base pressure decreases for cavity aspect ratio 1 and it increases for cavity aspect ratio 2, for L/D ratio upto 4. For L/D ratio more than 4, an increase in base pressure is always observed with increase in aspect ratio at all

supersonic Mach numbers and for all the area ratios tested. It is also observed that the length to diameter ratio beyond 6 is of no significant influence on the base pressure.

4. Base pressure is found to increase with increasing Mach numbers in the supersonic range. In subsonic range a decrease in base pressure is observed with increase in Mach number. Considerable oscillations were observed at few primary pressure ratios for flows with supersonic Mach numbers. Influence of cavities is less pronounced for flows with high Mach numbers. It was also found that the base pressure behaviour was smooth and without oscillations for flow from convergent nozzle in the Mach number range of 0.60—1.00.

5. The effect of cavity on wall pressure development in the enlarged duct is marginal at supersonic flows, whereas it is significant for subsonic Mach numbers. The wall pressure distribution in the enlarged duct revealed that the duct should have a definite minimum length for proper development of the flow.

6. The effect of aspect ratio on wall pressure is only marginal for supersonic Mach numbers, whereas it is considerable for subsonic Mach numbers resulting in the suppression of the oscillatory nature of wall static pressure field, thereby taking it smoothly from base pressure level to ambient atmosphere at the exit of the duct.

7. Total pressure loss increases with increase in Mach number, primary pressure ratio, area ratio and L/D ratio. In supersonic regime pressure loss increases for models with cavity aspect ratio 1 and decreases for models with cavity aspect ratio 2 for L/D ratio up to 4. Pressure loss is more for convergent-divergent

nozzles in comparison to nozzles with method of characteristics contour.

8. For a given primary pressure ratio and area ratio there exists a definite critical length of the enlargement giving a maximum secondary vacuum and a minimum pressure loss.

Appendix A

DATA ACCURACY

The main source of error in the measurement is due to fluctuations in the pressure values measured. Attention was paid to minimize the error in the measurement wherever possible. The presssure data reported are accurate upto 2% and they are repeatable within 3% even with the considerable oscillations. The geometrical parameters *viz.* the L/D ratio, area ratio and cavity aspect ratio are accurate upto approximately 2%.

Appendix B

SCOPE OF FURTHER RESEARCH

In the present investigation even though a wide range of Mach numbers and area ratios were covered, the maximum Mach number was 2.75. Further, the area ratio had only three representations in the range from 2 to 10. Also, the passive control used is of specific geometry in the form of annular rectangular grooves. The problem of sudden expansion requires much more investigation incorporating a more wider range of parameters because of the above limitations. The specific recommendations for the future work based on the experience gained with the present investigation are the following:

- It will be of interest to study the problem with Mach number higher than 2.75.
- The coverage of area ratio in finer increase around area ratio 3 is expected to give a better understanding of the flow field.
- The passive controls in the form of grooves with cross-section other than rectangular will be able to throw some more light on this problem.

- Study with two dimensional sudden expansion passeges will be of interest in the sense that the supersonic wave pattern at the base region can be optically visualized.

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